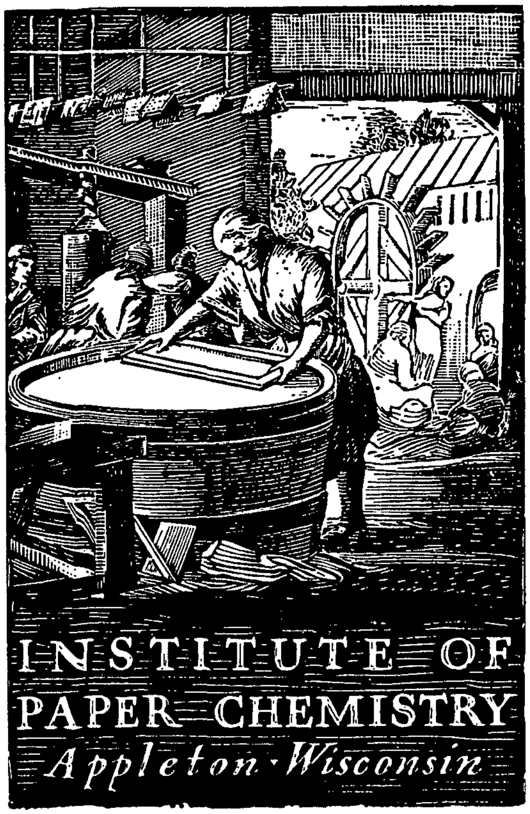

WOOD/BARK ADHESION AND METHODS OF REDUCING ADHESION IN HARDWOOD SPECIES

Project 2929

Report Three

A Progress Report

to

MEMBERS OF GROUP PROJECT 2929

January 28, 1972

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

WOOD/BARK ADHESION AND METHODS OF REDUCING ADHESION IN HARDWOOD SPECIES

SUMMARY

Using previously described field sampling techniques and the IPC Instron method of measuring wood/bark adhesion, the seasonal variation in wood/bark adhesion of white spruce, slash pine, shagbark hickory, and a southern source of eastern cottonwood was measured. Morphological observations were made on the seasonal changes that occurred in the "cambium zone" and the inner bark region and these changes were compared with variation in adhesion.

Peeling season wood/bark adhesion was uniformly low for all four species investigated and similar to the values obtained for the previously reported species. The failure zone was also consistently located in either the "cambium zone" or in the newly-formed nonlignified xylem and xylem initials just outside the cambium zone.

Dormant season adhesion values were considerably higher than the values obtained during the peeling season and varied greatly between species. For all the species investigated, the dormant season failure zone consistently occurred in the zone of newly-formed sieve tube (sieve cells in conifers) and parenchyma cells of the inner bark. Differences in adhesion appeared to be associated with the presence of phloem sclerenchyma elements (fibers and sclereids) in the innermost layers of the inner bark.

Because of the apparent importance of inner bark strength and the possible influence of both inner and outer bark strength on debarking, bark strength measurements were made on all eight species using the Instron testing procedure. Shagbark

hickory had the highest dormant season wood/bark adhesion and the highest inner bark strength of the species tested. Sugar maple and white birch had intermediate dormant season wood/bark adhesion but had very low inner bark strength. The differences encountered in the inner bark strength appear to be correlated with between-species morphological differences. The presence of bands of phloem fibers resulted in increased dormant season wood/bark adhesion and in increased inner bark strength (resistance to shear parallel to the grain). Low inner bark strength appeared to be related to the presence of numerous thick-walled but relatively short sclereids, crushed thin-walled sieve tubes and the lack of relatively long phloem fibers.

INTRODUCTION

Project 2929, "Wood/Bark Adhesion and Methods of Reducing Adhesion in Hardwood Species," began on March 15, 1970. Since the start of the program there has been increasing interest in "chipping in the woods" and "chipping at the stump." Recently, there has been demonstrated a chipping and harvesting system that essentially doubles the yield of wood chips from an acre of northern hardwoods. This is accomplished by utilizing the "so-called" nonmerchantable trees and by utilizing the complete tree. The system is capable of producing in excess of 400 tons (green weight) of wood per 8-hour day with a 6-man crew. This rapid rate of production is obtained by chipping prior to debarking and as a result of the ability of the chipper to handle multiple stems. The objective of this discussion is to point out that a "chipping in the woods" system exists. Improvements are expected, and to put these technological advances to best use, renewed efforts need to be made on ways of reducing wood/bark adhesion and ways of segregating wood/bark mixtures.

Project 2929, Progress Report One, described the methods developed for sampling and measuring wood/bark adhesion and provided seasonal measurements and morphological observations on white birch and quaking aspen. Progress Report Two presented seasonal wood/bark adhesion and related morphological observations for bur oak and sugar maple. Also described were preliminary observations on methods of reducing dormant-season wood/bark adhesion.

The report that follows describes the seasonal variation in wood/bark adhesion and the associated morphological observations made on: (1) shagbark hickory, (2) a southern source of cottonwood, (3) white spruce and (4) slash pine. Also included are measurements made on inner and outer bark strength of the 8 tree species under investigation.

EXPERIMENTAL METHODS AND MATERIALS

The experimental approach used consisted of periodically sampling locally grown pulpwood-sized white spruce and shagbark hickory and a source of eastern cottonwood and slash pine from near Mobile, Alabama.[1] Sampling varied with the species involved but generally extended from March through October. A small chain saw was used to remove wedge-shaped samples and, after trimming the samples to appropriate size, wood/bark adhesion was measured using the Instron tester. The samples collected in the Mobile, Alabama area (slash pine and eastern cottonwood) were collected on Monday afternoons and shipped moist by air freight in a container with dry ice. Such a procedure allowed testing the samples 64-72 hours after collection. A detailed description of field sampling procedures and the Instron testing procedure is available in Project 2929, Progress Report One. The procedure used measures shear parallel to the grain in the "cambium zone."[2] The test procedure has the disadvantage that, during the period of high adhesion, failure occurs in the bark, and when this happens, the values obtained must be interpreted as indicating that adhesion in the cambium zone and between wood and bark elements immediately adjacent to the cambium zone is "in excess of the test values obtained by the testing procedure."

Upon completion of the wood/bark adhesion measurements, representative samples were embedded, thin sections prepared, the sections stained and the failure surfaces examined for seasonal and between species differences. A detailed description of the microtechniques employed is given in Project 2929, Progress Report One.

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[1]The authors wish to acknowledge the valuable assistance of Mr. Andrew Djerf, International Paper Company, Mobile, Alabama, for his assistance in collecting and shipping the required samples of slash pine and cottonwood.

[2]Cambium zone — the true cambium consists of a single layer of dividing cells from which the xylem (wood) and secondary phloem (inner bark) arise. In this study the term "cambium zone" has been used to designate the true cambium plus all undifferentiated xylem and phloem cells immediately adjacent to the cambium.

In addition to the investigations described above, special samples were prepared that were used to measure the strength of the inner and outer bark. The only modification required was to relocate the cuts made that were the starting point for the failure. The cuts were made to overlap as previously described (Progress Report One) with the exception that the area of overlap, instead of being in the "cambium zone" was located in the inner bark or outer bark as required. Two dormant season samples were collected and six determinations were made of both inner and outer bark on each collection.

SEASONAL VARIATION IN WOOD/BARK ADHESION

SHAGBARK HICKORY

Anatomical Structure of Wood and Bark

Shagbark hickory is classified as a ring porous hardwood and the wood (xylem) is made up of fibers, vessels, parenchyma cells, and ray cells. The springwood vessels are conspicuously larger than the summerwood vessels and are distinct to the naked eye. The summerwood parenchyma is arranged in numerous continuous tangential lines and the rays are 1-5 seriate and are homogeneous to heterogeneous. The fibers of shagbark hickory vary moderately in cell wall thickness and are frequently gelatinous. The fibers range from 12 to 20 µm. in diameter and average approximately 1.2 mm. in length. The large springwood vessels range from 150 to 325 µm. in diameter while the summerwood vessels are 25 to 50 µm. in diameter. The numbers of vessels vary from 2 to 18 per $mm.^2$ Figure 1 illustrates the wood and bark structures described. The trees involved in this study were slow growing and the annual ring width appears to be about two-thirds of normal.

The inner bark (secondary phloem) of shagbark hickory is characterized by alternate wavy tangential layers or bands of gelatinous fibers and phloem parenchyma cells which are compactly arranged as illustrated in Fig. 1. The sieve tubes present are conspicuous, usually solitary (sometime in groups of 2 to 5) and are fairly uniformly distributed throughout the alternate tangential bands of phloem fibers and parenchyma cells. Phloem rays are fairly numerous, 1-5 seriate, up to 25 or more cells high and evenly distributed throughout the inner bark.

The sieve tubes are oval to polygonal in cross section and those cells located near the cambium zone average 75 µm. in diameter. The sieve tubes become more or less crushed in the outer regions of the secondary phloem. Examination of

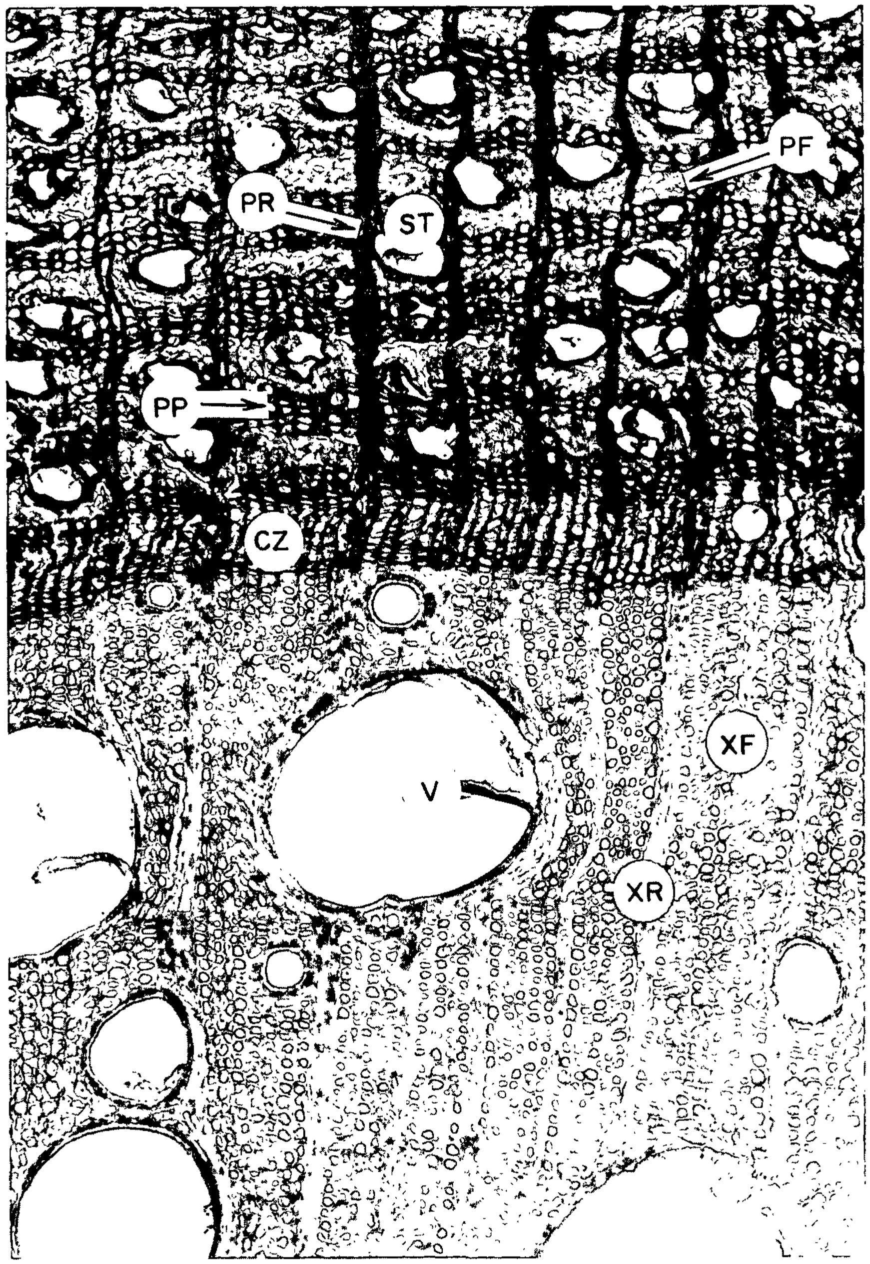

Figure 1. Cross Section of Shagbark Hickory from a May 24 Collection. Illustrated are a Number of Important Morphological Characteristics Including: Earlywood Xylem Vessels (V), Xylem Rays (XR), Xylem Fibers (XF), Active Cambium Zone (CZ), Thick-Walled Gelatinous Phloem Fibers (PF), Phloem Rays (PR), Phloem Parenchyma (PP) and Scattered Large Diameter Phloem Sieve Tubes (ST)

macerated bark of hickory indicate the sieve tubes to be approximately 0.6 to 0.7 mm. in length. The phloem parenchyma cells, arranged in tangential bands, one to three cells in width, are round to oval in cross section and average approximately 30 µm. in diameter. Parenchyma cells in a strand often contain solitary crystals.

The outstanding features of the inner bark of hickory are the large numbers of thick-walled gelatinous fibers and the absence of sclereids. The phloem fibers are aligned in narrow wavy tangential bands, 3 to 4 fibers in width. The cross section of the fibers is polygonal in shape and average approximately 20 µm. in diameter. Cell walls of the fiber cross sections appear to be separated into two distinct layers. The fibers average approximately 1.0 mm. in length and in view of their wavy arrangement, could be expected to contribute in a major way to the strength of the inner bark.

<u>Seasonal Variation in Wood/Bark Adhesion</u>

Seasonal sampling of shagbark hickory was initiated on March 29. Measurements were continued throughout the growing season and were discontinued after the August 16 sample was tested. Table I summarizes both the morphological observations made on the test specimens and the results of the measurements taken using the previously described Instron testing procedure. Figure 2 graphically presents the seasonal variation in shagbark hickory wood/bark adhesion as measured by shear parallel to the grain. Figure 3 illustrates the seasonal changes that occurred in the cambium zone and Fig. 4 demonstrates the accompanying changes that were found in the location of the zone of failure. In an effort to reduce costs and speed overall progress, the decision was made to section and describe the morphology of the test specimens for only a part of the dates upon which wood/bark adhesion measurements were made. The selection of the samples to be described was based upon the wood/bark adhesion values and the location of the zone of failure as estimated at the time the

TABLE I

SUMMARY OF OBSERVATIONS ON SEASONAL VARIATION
IN SHAGBARK HICKORY — APPLETON, WISCONSIN

Date	Adhesion, kg./cm.^{2} Average	Adhesion, kg./cm.^{2} Standard Deviation	Cambium Activity[a]	Width Cambium Zone	New Xylem Cells Total No.	New Xylem Cells No. Non-lignified	No. Immature Phloem Cells	Location of Zone of Failure	Additional Zones of Apparent Weakness
3/29/71	21.8	1.39	D	4-5	0	0	3-4	Inner bark-last formed parenchyma & fiber bands just outside the cambium zone	Cambium zone
4/12/71	32.0	1.25	D	4-5	0	0	3-4	Same as above	Cambium zone
4/26/71	24.2	1.38	D	4-5	0	0	3-4	Same as above	Cambium zone
5/10/71	8.3	0.49	A[b]	4-5	0	0	3-4	Cambium zone	Immature phloem
5/24/71	3.0	0.29	A	14-16	0	0	3-4	Immature xylem cells	Cambium zone
6/14/71	4.6	0.49	A	--	--	--	--	Cambium zone	Immature phloem
7/12/71	17.0	1.27	D	4-5	18-20	15-16	3-4	Cambium zone	Immature xylem & immature phloem
7/26/71	34.0	1.71	D	4-5	13-16	0	3-4	Inner bark — last formed parenchyma and phloem fibers just outside the cambium zone	Cambium zone
8/16/71	32.2	1.85	D	4-5	13-16	0	3-4	Same as above	Cambium zone

[a] A = active, D = dormant.
[b] Cambium activity just starting.

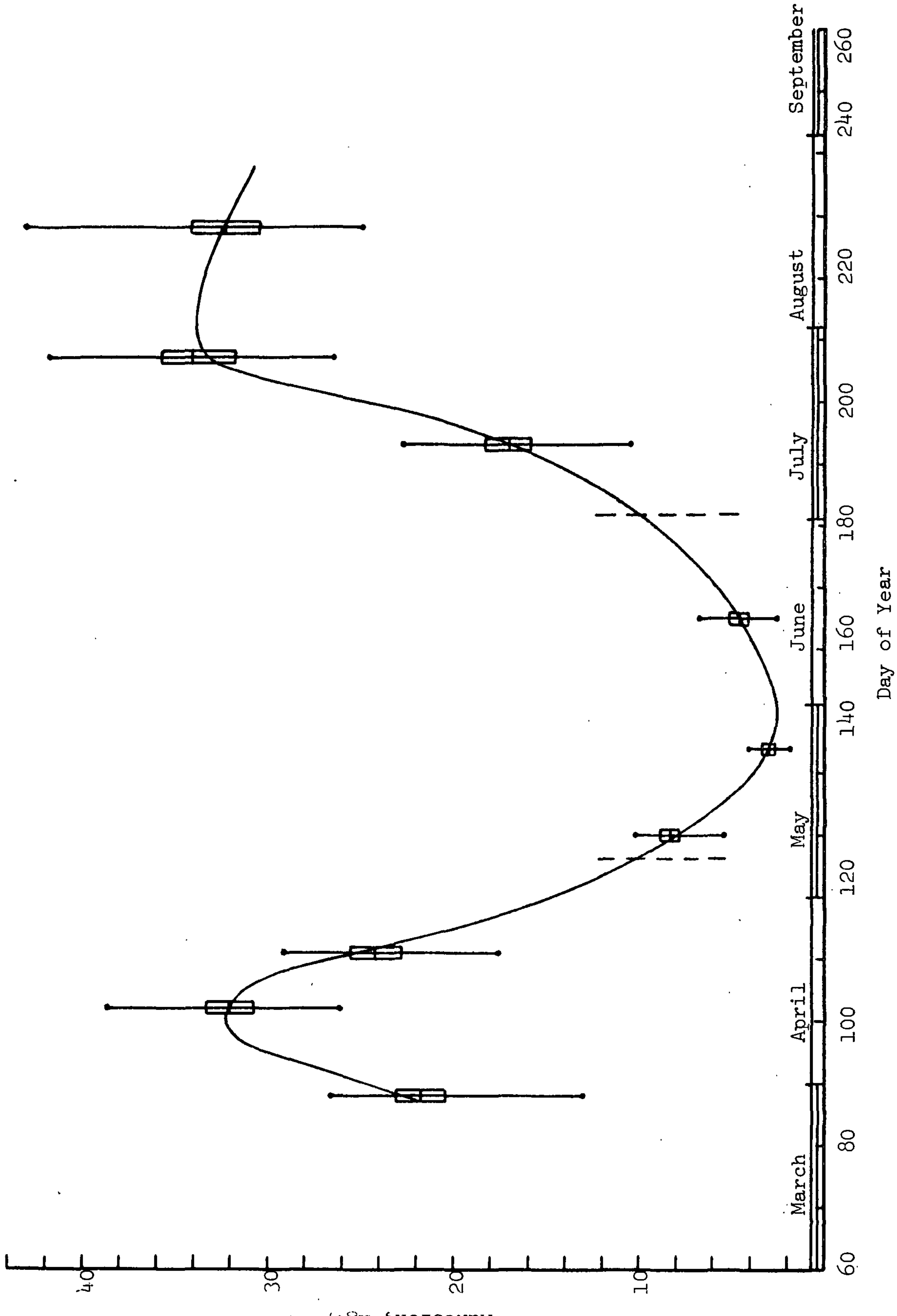

Figure 2. Seasonal Variation in Wood/Bark Adhesion of Shagbark Hickory. Shown for Each Sampling Date is the Range, Mean and One Standard Deviation on Each Side of Mean. The Vertical Dashed Lines Indicate the Estimated Start and End of the Peeling Season

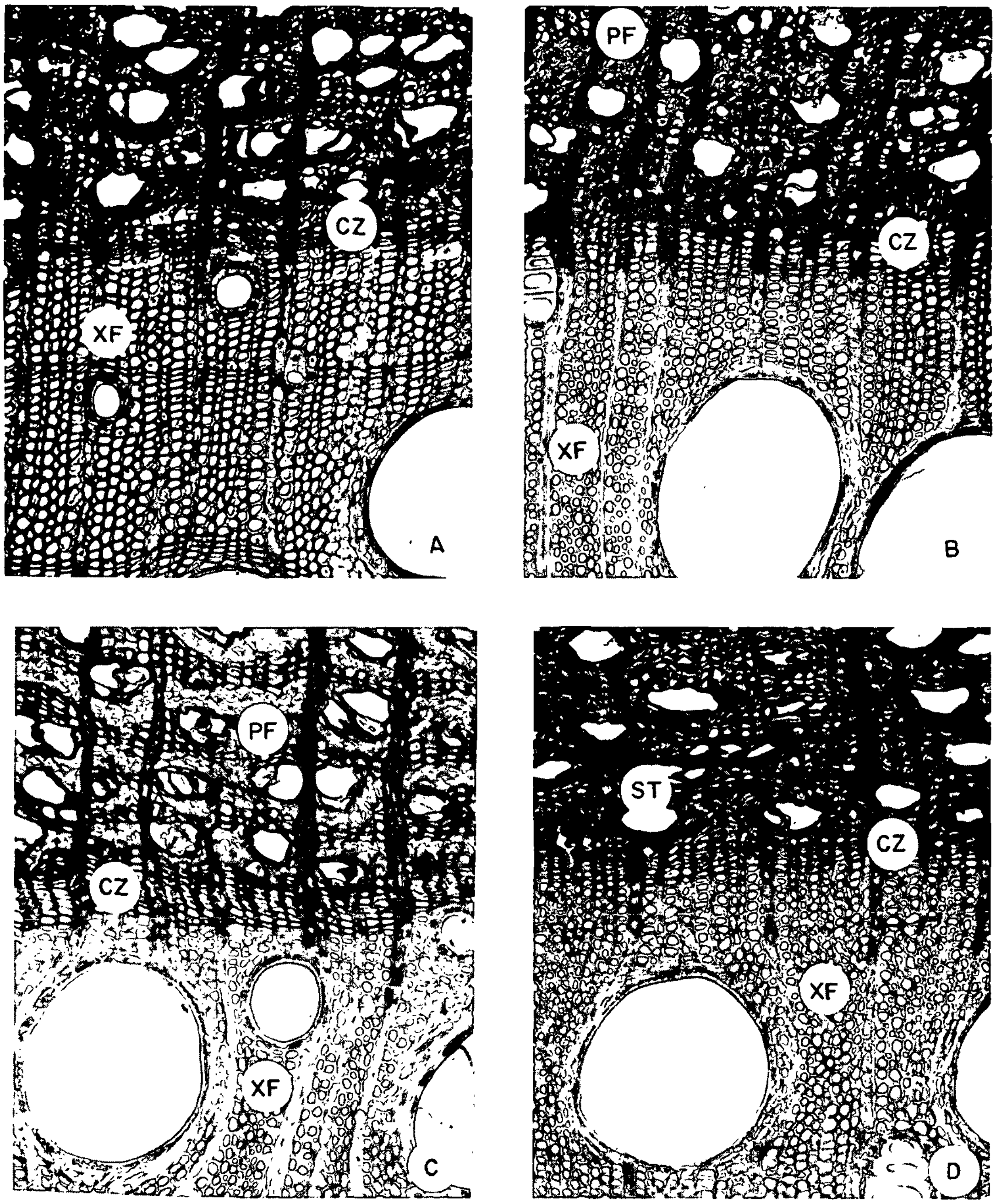

Figure 3. Illustrated, Using Cross Sections of Shagbark Hickory, are the Seasonal Changes that Occurred in the Cambium Zone; A — April 12 Collection, Cambium Dormant, Cambium Zone (CZ) 4-5 Cells in Width; B — May 10 Collection, Cambium Activity Just Starting, Cambium Zone Still 4-5 Cells in Width; C — May 24 Collection, Cambium Active, Cambium Zone 6-8 Cells in Width and None of the Newly-Formed Xylem Cells Show Lignification; D — August 16 Collection, Cambium Zone Dormant, 4-5 Cells in Width, Lignification of Xylem Fibers (XF) of Last Growth Ring Complete. Also Illustrated are Phloem Fibers (PF) and Sieve Tubes (ST) of the Inner Bark

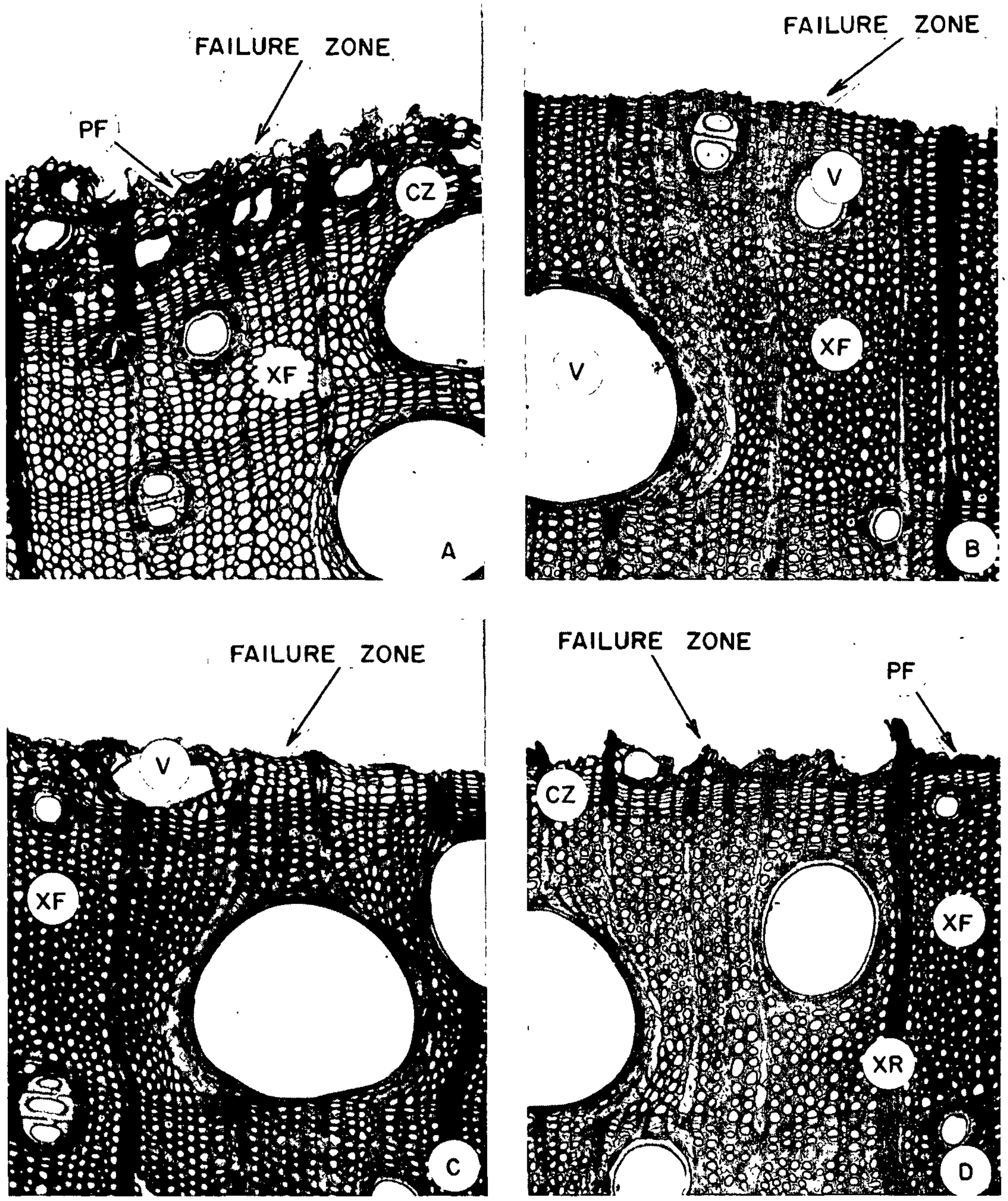

Figure 4. Illustrated, Using Cross Sections of Shagbark Hickory, are the Seasonal Changes that Occurred in the Location of the Failure Zone; A — April 12 Collection, Failure Occurred in Inner Bark Between Bands of Phloem Parenchyma and Phloem Fibers (PF); B — May 10 Collection, Failure in the Cambium Zone; C — May 24 Collection, Failure in the Cambium Zone and Nonlignified Xylem Initials; D — August 16 Collection, Failure in the Inner Bark Phloem Parenchyma and Phloem Sieve Tube Zone and Along Phloem Fiber Band (PF). Also Illustrated are Xylem Fibers (XF), Xylem Rays (XR) and Vessels (V)

adhesion measurements were made. Described below are the observations made on the seasonal morphological changes that were associated with changes in wood/bark adhesion.

March 29 — Cambium dormant; morphology of the test specimens not described; failure occurred in the inner bark and apparently in the same zone as on April 12. Estimated wood/bark adhesion in the cambium zone was in excess of 21.8 kg./cm.^{2}.

April 12 — Cambium dormant; cambium zone 4-5 cells in width; failure occurred in the rows of phloem fibers and parenchyma cells immediately adjacent to the cambium zone. In part of the failure zone, one or two layers of phloem fibers and parenchyma cells were located between the break and the cambium. (Fig. 4A). Estimated adhesion in the cambium zone was in excess of 32 kg./cm.^{2}

April 26 — Cambium dormant; morphology of the test specimen not described; failure occurred in the inner bark and was apparently in the same zone as on April 12. Estimated adhesion in the cambium zone was in excess of 24.2 kg./cm.^{2}

May 10 — Cambium dormant; cambium zone 4-5 cells in width; adhesion values indicate cambium activity just starting; failure zone occurred in the cambium zone at the interface between the cells involved (Fig. 4B); adhesion in the cambium zone was 8.3 kg./cm.^{2}

May 24 — Cambium active; cambium zone, which is primarily new xylem initials, is 14-16 cells in width; none of the new xylem initials show any lignification; failure occurred in the xylem initials of the cambium zone; adhesion was 3.0 kg./cm.^{2}

June 14 — Cambium active; morphology of the test specimen not examined; failure believed to have occurred in the new xylem initials just inside the cambium zone; adhesion in the cambium zone was 4.6 kg./cm.^{2}

July 12 — Cambium dormant; cambium zone 4-5 cells in width; lignification is complete on only the earliest few cells (fibers and vessels) of the current growth ring; apparently cambium activity quite recently stopped; failure occurred in the cambium zone; adhesion in the cambium zone was 17.0 kg./cm.^{2}

July 26 — Cambium dormant; morphology of the test specimens not examined; failure believed to have occurred in the inner bark in the same location as described for August 16. Estimated wood/bark adhesion in the cambium zone was in excess of 34.0 kg./cm.^{2}

August 16 — Cambium dormant; cambium zone is 4-5 cells in width; lignification of the fibers and vessels of the current year's growth appears to be complete; failure occurred in the inner bark between the last-formed phloem fibers and the phloem parenchyma cells located immediately adjacent to the cambium zone. Estimated wood/bark adhesion in the cambium zone was in excess of 32.2 kg./cm.^{2}

Bark adhesion in and near the cambium zone varied from 3.0 kg./cm.^{2} on May 24 to 34.0 kg./cm.^{2} on July 26. The dormant season adhesion values were the highest measured for any of the 8 species investigated. Based upon wood/bark adhesion measurements and morphological observations, the peeling season for shagbark hickory was estimated to extend from about May 6 to July 1 (wood/bark adhesion less than 10.0 kg./cm.^{2}). The 55-day peeling season was somewhat less than expected and appears to have been influenced by the relatively slow growth of the trees involved.

Prior to the "peeling season," failure of the test specimens occurred in the inner bark (secondary phloem) between bands of thick-walled phloem fibers and phloem parenchyma cells in the proximity of the cambium zone. Often failure occurred outside one or two bands of phloem fibers (Fig. 4A). During the first part of the peeling season the zone of failure occurred in the cambium zone. Later in the peeling season, as in the case of the other hardwoods studied, the zone of failure moved into the zone of newly-formed immature xylem cells just outside the cambium. This latter change is more difficult to detect when the trees are slow growing. During the dormant period of late summer, the zone of failure again occurred in the inner bark and in the same zone as described for the early spring measurements.

Dormant season wood/bark adhesion of the cambium zone appears to be strongly correlated with phloem maturation and the morphology of the innermost layers of the inner bark. As was discussed in Progress Report Two, phloem maturation is very complicated compared to the simplicity of xylem maturation where all cells produced within a year mature that same year. Only a quarter of the phloem cells produced within one season mature before winter dormancy. The remaining cells initiate or complete maturation the following spring prior to resumption of cambium activity.

Observations made on dormant season cross sections indicate the primary zones of weakness in hickory are the undifferentiated cells of the cambium zone and the nonlignified, partially mature phloem parenchyma and sieve tubes just outside the cambium. The very high dormant season wood/bark adhesion appears to be related to the presence of compactly arranged wavy bands of thick-walled phloem fibers and the scattered arrangement of the thin-walled sieve tube elements. Treatments aimed at reducing adhesion should be concentrated primarily on the cambium zone and the innermost layers of the inner bark.

WHITE SPRUCE

Anatomical Structure of Wood and Bark

The wood (xylem) of white spruce is very uniform in appearance (see Fig. 5) and consists of tracheids aligned in distinct radial rows, uniseriate and fusiform rays and longitudinal and transverse resin canals. The growth rings of white spruce are distinct, delineated by the contrast between latewood and earlywood of the succeeding growth rings. The springwood zone is usually several times wider than the summerwood zone, grading gradually into summerwood. The tracheids have an average diameter of 25-30 μm. and an average length of 3.5 mm. The average cell wall thickness of the springwood fibers is less than 1.0 μm. while the summerwood tracheids have an average cell wall thickness of 3-4 μm.

The uniseriate rays are fine and numerous. They are 1-16+ cells in height. The fusiform rays, up to 16+ cells in height, are scattered, with one or rarely two transverse resin canals. Ray tracheids are present in both types of rays and usually restricted to one row on the upper or lower margin. The longitudinal resin canals average 50-60 μm. in diameter, while the transverse resin canals average less than 30 μm. in diameter. The ducts are encircled by epithelial cells and those in the heartwood may occasionally be occluded with tylosoids.

The inner bark (secondary phloem) of white spruce is made up of sieve cells, parenchyma cells, sclereids, ray cells, and horizontal resin canals (see Fig. 5). The sieve cells are aligned in regular radial rows. Usually there are 14-16 sieve cells in a row before being interrupted by 1-3 tangential lines of parenchyma cells. Small groups of sclereids are aligned in sporadic discontinuous bands. Phloem rays are both uniseriate and fusiform. Horizontal resin canals which average approximately 250 μm. in diameter are common in the fusiform rays.

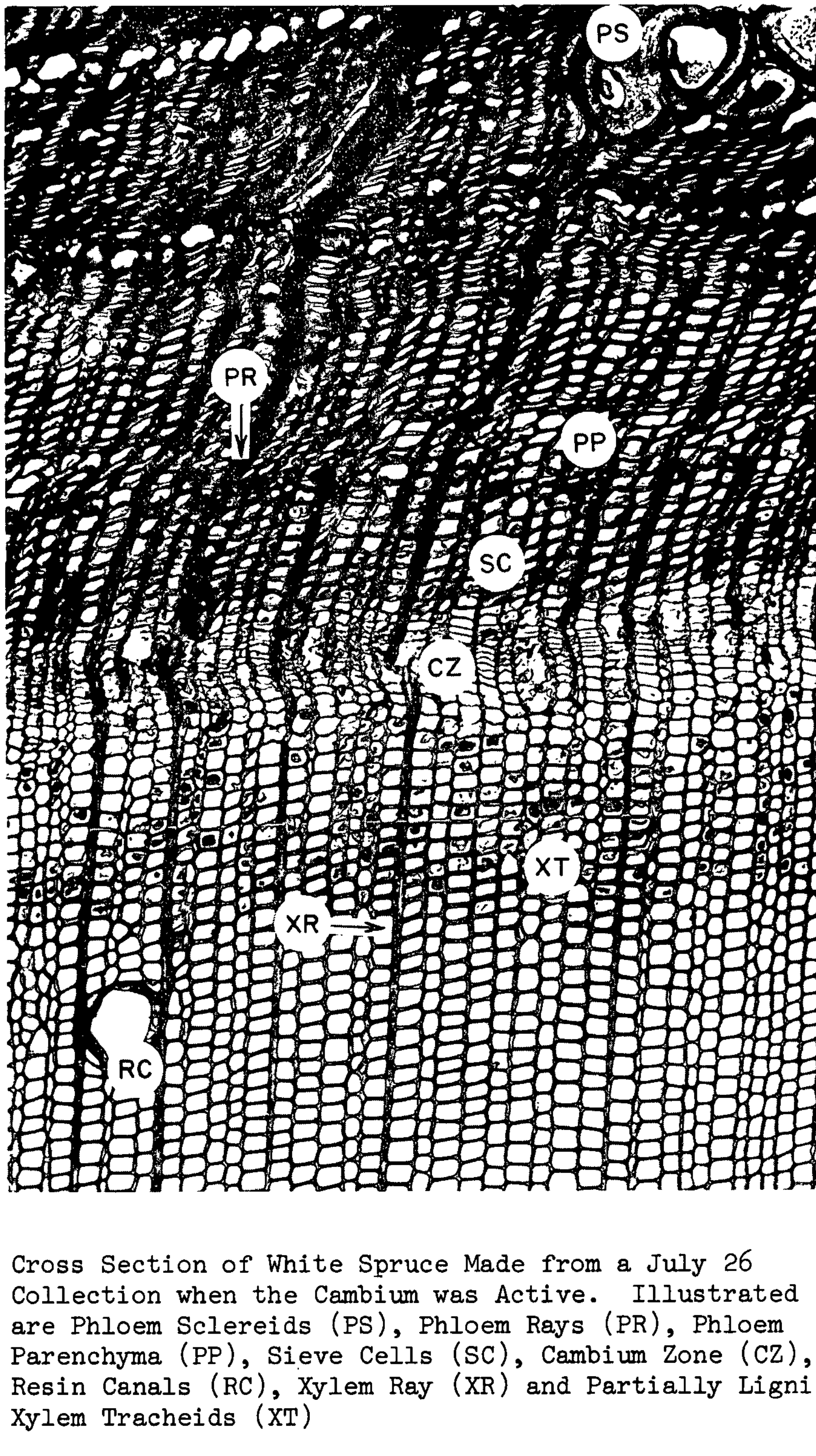

Figure 5. Cross Section of White Spruce Made from a July 26 Collection when the Cambium was Active. Illustrated are Phloem Sclereids (PS), Phloem Rays (PR), Phloem Parenchyma (PP), Sieve Cells (SC), Cambium Zone (CZ), Resin Canals (RC), Xylem Ray (XR) and Partially Lignified Xylem Tracheids (XT)

The sieve cells in the phloem of white spruce appear rectangular in cross section, their radial and tangential dimensions averaging approximately 20 and 40 µm., respectively. The length of the sieve cells of spruce according to Chang (1) average between 3.0 and 3.5 mm. in length. The walls of the sieve cells are approximately 1-2 µm. in thickness. The newly formed phloem parenchyma cells are approximately the same shape and size as the adjacent sieve cells in cross section but become expanded considerably after a few seasons of growth. The sclereids are transformed from the phloem parenchyma and are aggregated in small groups. The size of the larger sclereid groups may have a radial dimension of 0.3 mm., a tangential dimension of 1.0 mm., and a height of 1-2 mm. The individual cells are thick walled (25^{+} µm.), irregular in shape and sometimes branched.

Seasonal Variation in Wood/Bark Adhesion

Seasonal sampling of white spruce wood/bark adhesion was initiated on March 29. Measurements were made throughout the growing season and were discontinued after the September 7 samples were tested. Table II summarizes both the morphological observations made on the test specimens and the results of the measurements taken using the previously described Instron testing procedure. As discussed in the section on hickory, not all samples that were tested for adhesion were examined morphologically. Figure 6 graphically presents the seasonal variation in white spruce wood/bark adhesion measurements as measured by shear parallel to the grain. Figure 7 illustrates the seasonal changes that occurred in the cambium zone and Fig. 8 demonstrates the accompanying changes that were found in the location of the zone of failure. Described below are the observations made on seasonal morphological changes that were associated with changes in wood/bark adhesion.

TABLE II

SUMMARY OF OBSERVATIONS ON SEASONAL VARIATION IN WHITE SPRUCE — APPLETON, WISCONSIN

Date	Adhesion, kg./cm.^{2}		Cambium Activity[a]	Width Cambium Zone	New Xylem Cells		No. Immature Phloem Cells	Location of Zone of Failure	Additional Zones of Apparent Weakness
	Average	Standard Deviation			Total No.	No. Non-lignified			
3/29/71	8.3	0.40	D	5-6	0	0	5-6	Inner bark — last formed sieve and/or parenchyma cells	Cambium zone
4/12/71	11.2	0.64	D	5-6	0	0	5-6	Same as above	Cambium zone
4/26/71	7.1	0.56	D	5-6	0	0	5-6	Cambium zone adjacent to last year's mature xylem cells	Inner bark adjacent to cambium zone
5/10/71	3.7	0.59	A	5-6	0	0	5-6	Same as above	Same as above
6/15/71	3.4	0.37	A	--	--	--	--	Cambium zone	--
7/12/71	5.5	0.31	A	--	--	--	--	Cambium zone	--
7/26/71	5.1	0.33	A	10-12	55+	16-18	3-4	Xylem between newly formed cells and adjacent immature but partly lignified tracheids	Inner bark as on 4/26 and 5/10
8/16/71	12.3	0.66	D	--	--	--	--	Newly formed sieve cells of inner bark	--
9/7/71	12.4	0.75	D	5-6	55+	0	10-14	Inner bark — similar to 3/29 above	Cambium zone

[a] A = active, D = dormant.

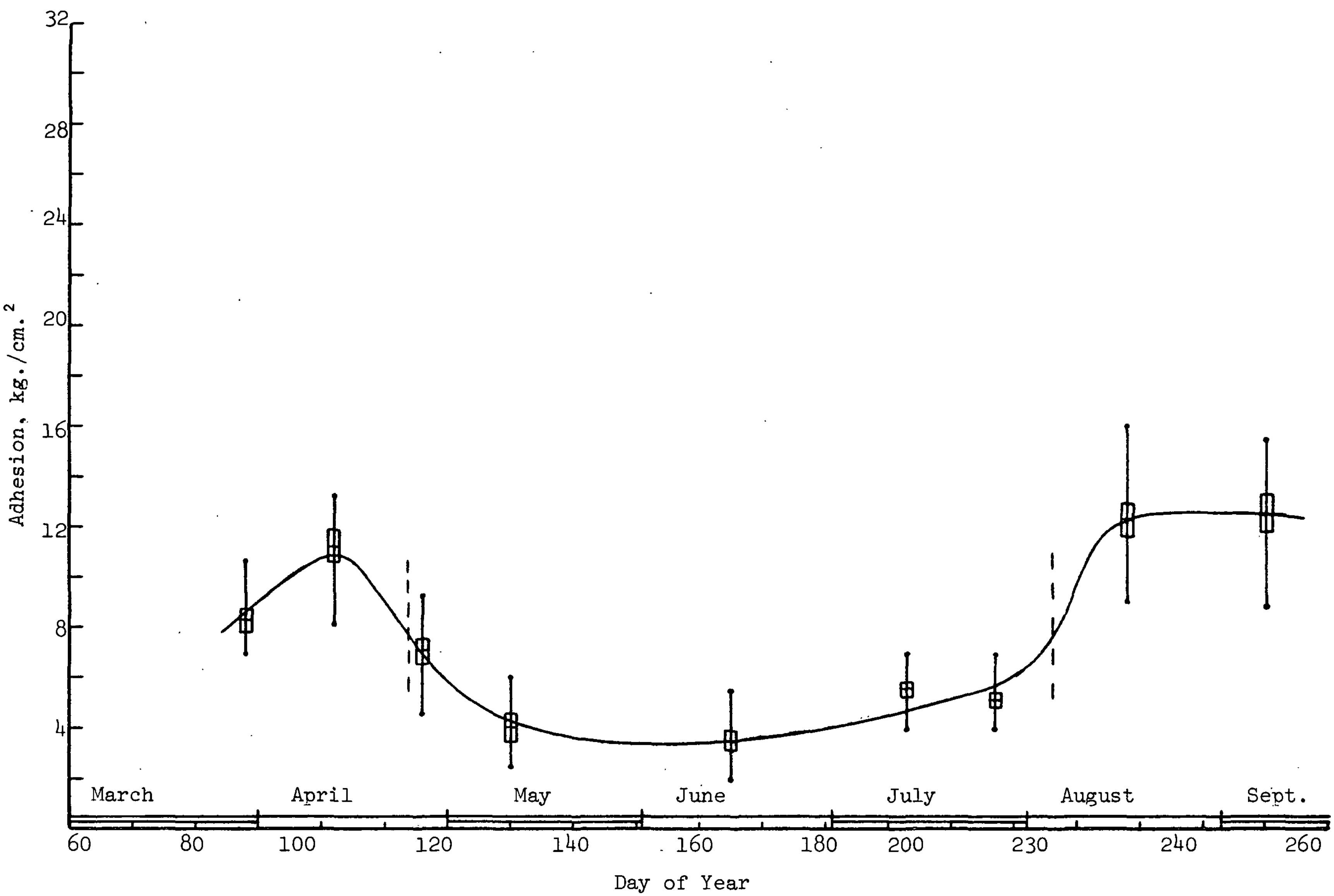

Figure 6. Seasonal Variation in Wood/Bark Adhesion of White Spruce. Shown for each Sampling Date is the Range, Mean and One Standard Deviation on Each Side of the Mean. The Vertical Dashed Lines Indicate the Start and End of the Peeling Season

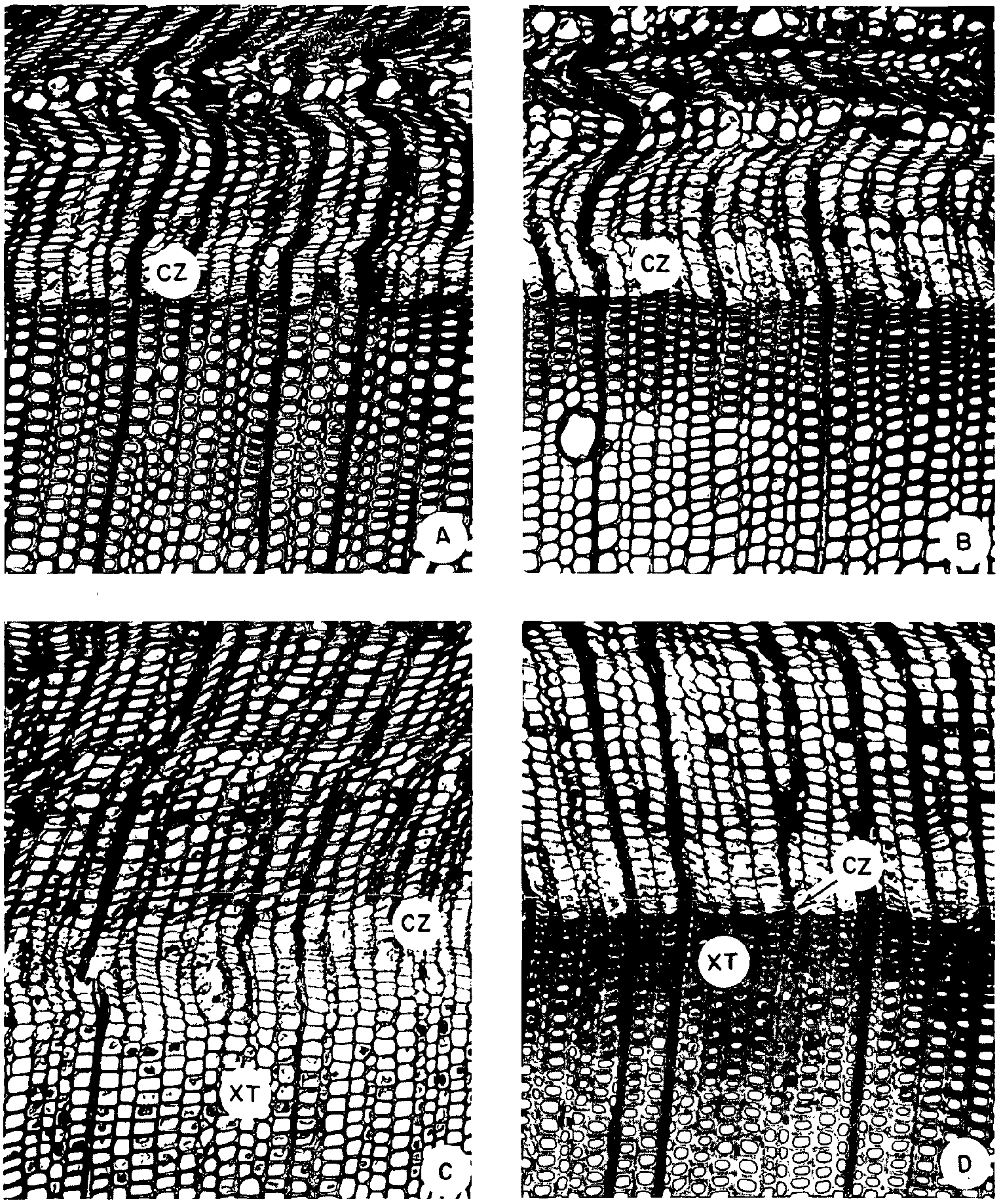

Figure 7. Illustrated, Using Cross Sections of White Spruce are the Seasonal Changes that Occurred in the Cambium Zone; A — March 29 Collection, Cambium Dormant, Cambium Zone (CZ) 5-6 Cells in Width; B — May 10 Collection, Cambium Appears Dormant but Apparently Activity Has Just Started, Cambium Zone (CZ) 5-6 Cells in Width; C — July 26 Collection, Cambium Active, Cambium Zone (CZ) 10-12 Cells in Width, Lignification of Recently Formed Xylem Tracheids (XT) is Just Starting; D — September 9 Collection, Cambium Dormant, Cambium Zone (CZ) 5-6 Cells in Width, Xylem Tracheids (XT) Fully Mature and Lignification Complete

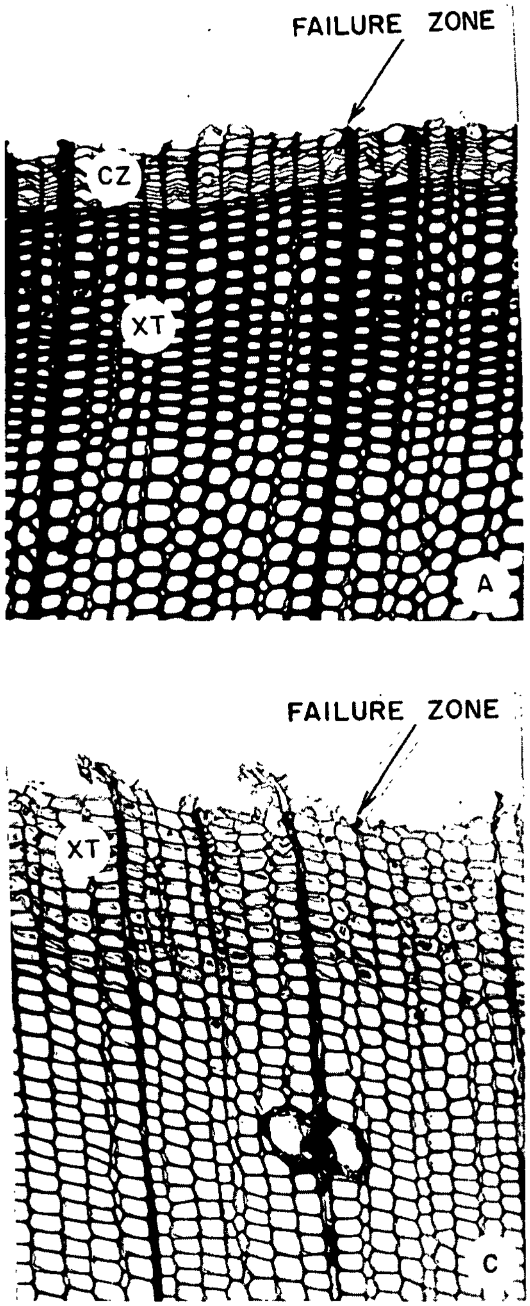

Figure 8. Illustrated are the Seasonal Changes in the Location of the Zone of Failure in White Spruce; A — March 29 Collection, Failure in the Inner Bark Area of Phloem Sieve and/or Parenchyma Cells Just Outside the Cambium Zone (CZ); B — May 10 Collection, Failure in the Cambium Zone (CZ) Between the Cambium Initials and the Fully Mature Previous Season Xylem Tracheids (XT); C — July 26 Collection, Failure in the Xylem Between the Xylem Initials and the Adjacent Immature Tracheids (XT); D — September 7 Collection, Failure Occurred in the Sieve Cells (SC) of the Inner Bark, Starting Near the Cambium Zone (CZ) and Going as much as 0.5 mm. into the Inner Bark

March 29 — Cambium dormant; cambium zone 5-6 cells in width; failure occurred in phloem between the last-formed phloem sieve cells and/or parenchyma cells adjacent to the cambium zone (Fig. 8). Estimated adhesion in the cambium zone was in excess of 8.3 kg./cm.^{2}

April 12 — Cambium dormant; cambium zone 5-6 cells in width; failure zone in inner bark region as on March 29. Estimated adhesion in cambium zone was in excess of 11.2 kg./cm.^{2}

April 26 — Cambium dormant; cambium zone 5-6 cells in width; failure occurred between cells in the cambium zone and adjacent to the last-formed lignified xylem cells. Wood/bark adhesion was in excess of 11.1 kg./cm.^{2}

May 10 — Cambium still appears dormant; cambium zone 5-6 cells in width; failure occurred in the cambium zone between cambium initials and the last formed fully mature summerwood tracheids of last years' growth. Wood/bark adhesion was only 3.7 kg./cm.^{2}, indicating cambium activity was just beginning.

June 14 — Cambium active; morphology of test samples not described; failure appears to have occurred in the cambium zone; wood/bark adhesion was 3.4 kg./cm.^{2}

July 12 — Cambium active; morphology of the test samples not described; failure appears to have occurred in the cambium zone; wood/bark adhesion was 5.1 kg./cm.^{2}

July 26 — Cambium active; cambium zone consists of 10-12 undifferentiating cells; tracheids located 16-18 cells from cambium zone have thicker walls indicating the start of latewood formation. Lignification and secondary thickening has not been completed in the last-formed 6-8 tracheids adjacent to the cambium zone. Failure occurred in the xylem between the xylem initials and the adjacent immature tracheids that show some cell wall lignification. Wood/bark adhesion was 5.1 kg./cm.^{2}

August 16 — Cambium dormant; morphology of test samples not examined by sectioning; failure is believed to have occurred in the newly-formed sieve cells of the inner bark; estimated wood/bark adhesion in the cambium zone was in excess of 12.3 kg./cm.^{2}

September 7 — Cambium dormant; cambium zone 5-6 cells in width; all xylem cells are fully mature and lignification is complete. Failure occurred in the sieve cells of the inner bark (secondary phloem) region starting near the cambium and going as much as 0.5 mm. into the inner bark.

The bark peeling season for white spruce growing in a plantation near the Institute was estimated to have started on April 24 (adhesion values less than 7.5 kg./cm.^{2}) and extended until August 4. The length of the peeling season during 1971 (102 days) was longer than most other species previously examined and approximately the same as for bur oak growing near Appleton, Wisconsin in 1970. Adhesion values during the dormant season averaged 11.0 kg./cm.^{2}, while during the peeling season the wood/bark adhesion varied from 3.4 to 7.1 and averaged 5.0 kg./cm.^{2}

The zone of failure started out during the spring dormant season in the inner bark sieve and parenchyma cells. At the beginning of the peeling season the failure began to occur in the cambium zone and in the newly-formed xylem elements just outside the cambium. At the conclusion of the peeling season the zone of failure moved back out to the inner bark region.

The relatively simple structure of the wood and bark of spruce and the very consistent results obtained from the wood/bark adhesion measurements require very little interpretation. Both the dormant season and peeling season adhesion values were relatively low and the location of the zone of failure and the zones of weakness were similar to the information obtained from species previously investigated in this project.

EASTERN COTTONWOOD

Anatomical Structure of Wood and Bark

The general structure of the wood (xylem) of eastern cottonwood is similar to that of the aspens. The wood is semiring to diffuse porous. The growth rings are distinct but inconspicuous and often very wide. The small xylem vessels are barely visible with the naked eye in the springwood and decrease gradually in size through the summerwood. The vessels are solitary or in radial rows of two or more. The parenchyma cells are terminal, the narrow light-colored lines being more or less distinct. The rays are very fine, scarcely visible with a hand lens and are unstoried, uniseriate, and essentially homogeneous.

The fibers, thin to medium thick-walled, occasionally gelatinous, range from 25-40 µm. in diameter, with an average length of approximately 1.0 mm. The large springwood vessels are 100-150 µm. in diameter while the summerwood vessels are about half this size. There are between 30-145 vessel elements per square millimeter. Figure 9 illustrates typical dormant season appearance of the inner bark and wood of eastern cottonwood.

The inner bark (secondary phloem) of cottonwood is composed of thin-walled sieve tubes which may be solitary but are mostly in small groups of 2 to 5, together with companion cells and phloem parenchyma. These cells are bounded radially by uniseriate phloem rays and tangentially by bands of phloem sclerenchyma. The sieve tubes are oval to polygonal in cross section and vary from 25 µm. to 50 µm. in diameter.

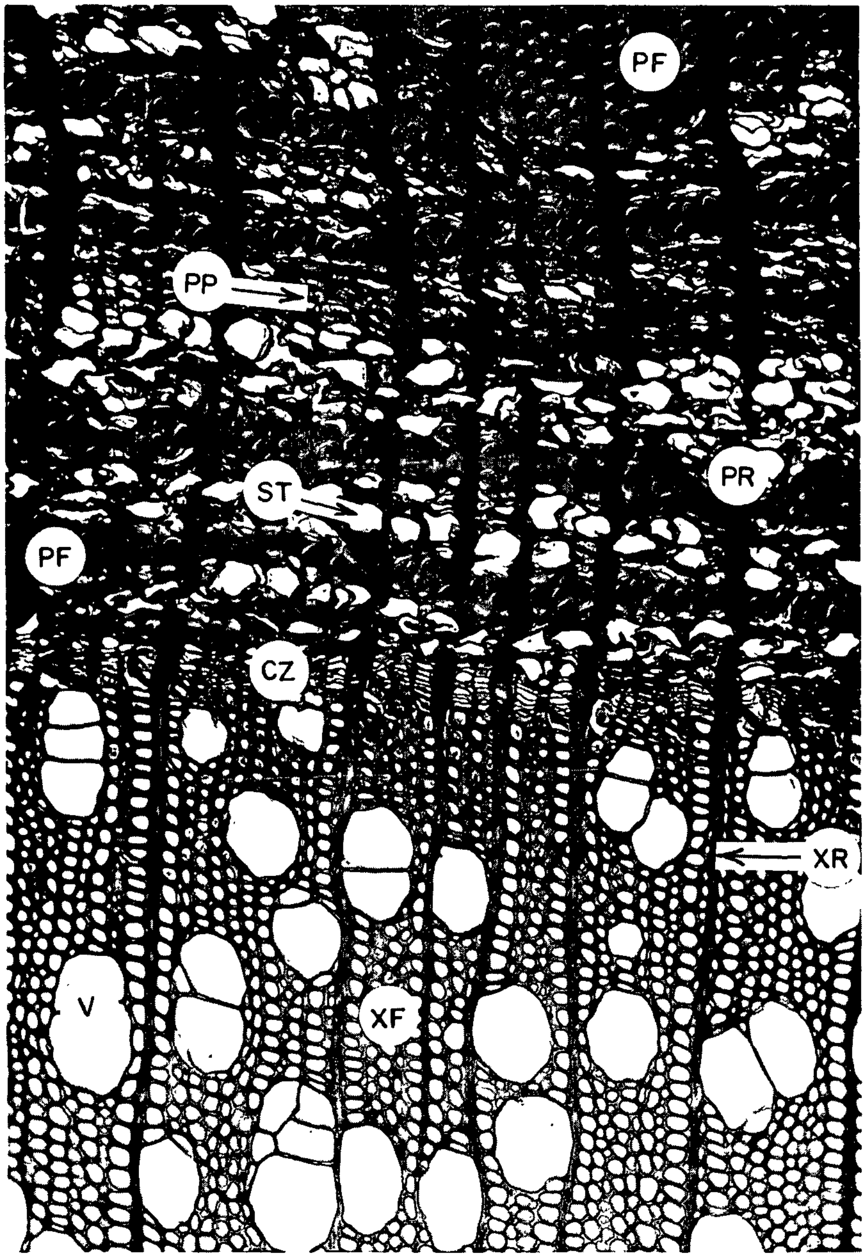

Figure 9. Cross Section of Cottonwood Wood and Bark When the Cambium was Dormant (8/16/71). Illustrated are Phloem Fiber (PF), Phloem Ray (PR), Phloem Parenchyma (PP), Sieve Tubes (ST), Cambium Zone (CZ), Xylem Fibers (XF), Vessels (V), and Xylem Ray (XR)

The parenchyma cells are distributed in a more or less reticulate formation among the sieve tubes. The cross section of these cells is round to oval and average approximately 20 µm. in diameter.

Narrow tangential bands of phloem fibers closely and evenly spaced are characteristic of the inner bark of the species. The bands of fibers average approximately 60 µm. in radial dimension and consist of mostly 3-4 fibers in radial rows. Occasionally, a small portion of the band may be more than 200 µm. in width and consist of 10-12 fibers in radial rows. The fiber cell walls are very thick, about 10 µm. and the lumen is narrow, approximately 2-3 µm. The cross sections are polygonal and average approximately 20 µm. in diameter at the broadest portion. The fibers average approximately 1.0 mm. in length. Small groups of thick-walled sclereids appear in the outer part of the inner bark for the specimens examined.

Seasonal Variation in Wood/Bark Adhesion

Seasonal sampling of eastern cottonwood wood/bark adhesion was initiated in the Mobile, Ala. area on Feb. 1. Measurements, which were made periodically throughout the growing season, were discontinued after the August 30 samples were evaluated. Table III summarized the morphological observations and the results of the measurements taken using the previously described Instron testing procedure. Figure 10 graphically presents the seasonal variations in wood/bark adhesion. Figure 11 illustrates the seasonal changes that occurred in the cambium zone and Fig. 12 demonstrates the accompanying changes that developed in the location of the zone of failure. The seasonal changes in wood/bark adhesion of cottonwood did not follow as orderly a pattern as has been encountered with the other species investigated. Adhesion increases were noted on March 15 and March 29. The increased adhesion on these two dates apparently resulted because of the flooding of the

TABLE III

SUMMARY OF OBSERVATIONS ON SEASONAL VARIATION
IN EASTERN COTTONWOOD, MOBILE, ALABAMA

Date	Adhesion, kg./cm.² Average	Standard Deviation	Cambium Activity[a]	Width Cambium Zone	New Xylem Cells Total No.	No. Non-lignified	No. Immature Phloem Cells	Location of Zone of Failure	Additional Zones of Apparent Weakness
2/1/71	7.2	0.37	D	3-4	0	0	2-3	Inner bark, between sieve tubes and parenchyma cells and last formed band of phloem fibers	Cambium zone
2/15/71	6.4	0.38	D	3-4	0	0	2-3	Same as 2/1	Cambium zone
3/1/71	6.3	0.38	D	3-4	0	0	2-3	Same as 2/1	Cambium zone
3/15/71	9.2	0.57	D	3-4	0	0	2-3	Same as 2/1	Cambium zone
3/29/71	8.1	0.37	D	3-4	0	0	2-3	Same as 2/1	Cambium zone
4/19/71	6.2	0.44	A	--	--	--	--	Estimated to be as on 5/10	Cambium zone and immature inner bark cells
5/10/71	5.1	0.45	A	12-14	30-35	6-8	4-6	Xylem between newly formed cells and adjacent immature but partially lignified vessels and fibers	Same as above
6/14/71	5.1	0.25	A	12-14	--	--	--	Same as above	Same as above
7/12/71	4.4	0.27	A	12-14	50+	6-8	6-8	Same as above	Same as above
8/2/71	9.8	1.22	D	--	--	--	--	Estimated to be as on 2/1	Cambium zone
8/16/71	13.5	0.70	D	3-4	70+	0	2-3	Inner bark just outside cambium zone, as occurred on 2/1	Cambium zone
8/30/71	12.6	0.65	D	3-4	70+	0	2-3	Same as above	Cambium zone

[a] A = active, D = dormant.

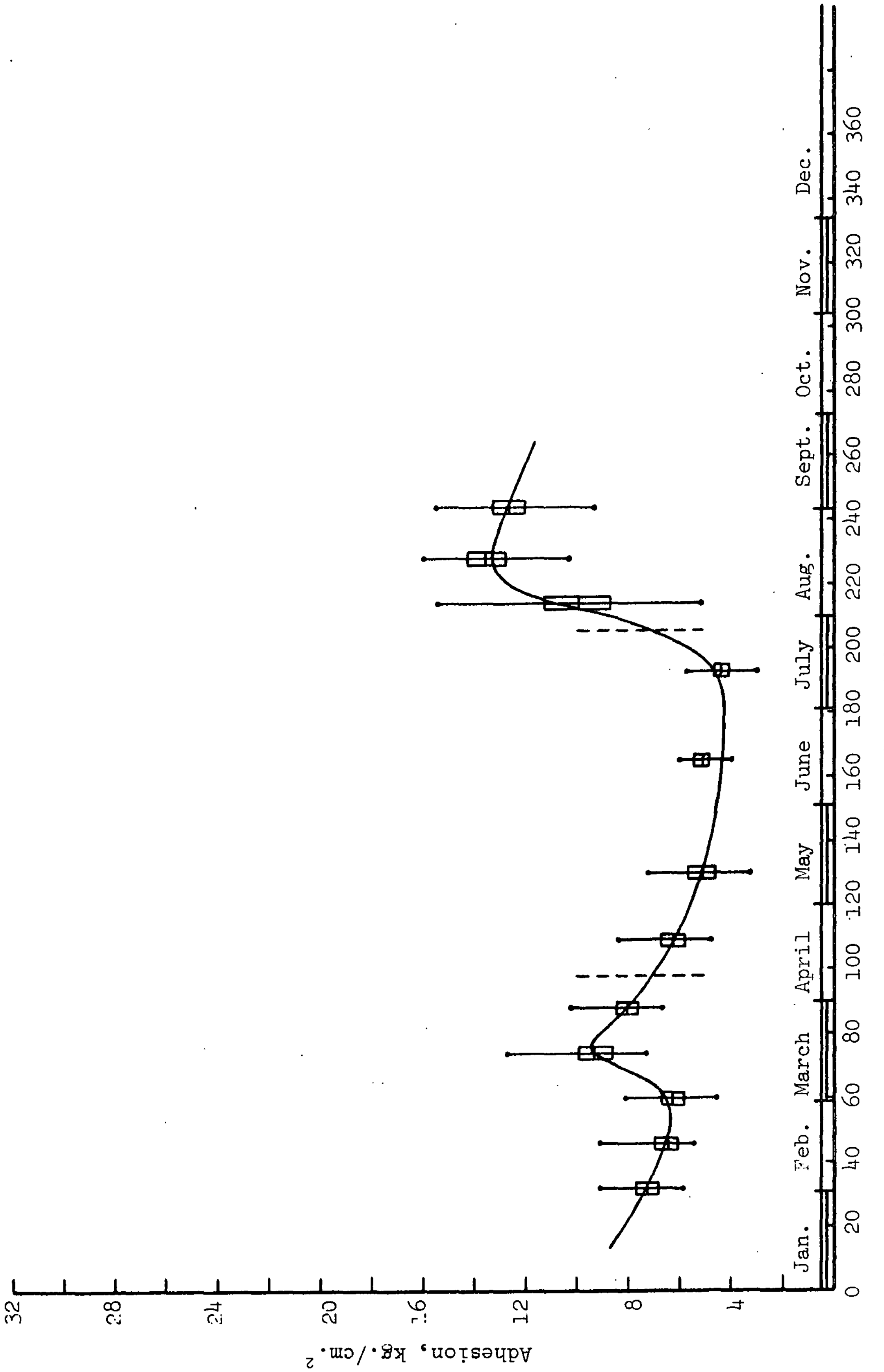

Figure 10. Seasonal Variation in Wood/Bark Adhesion of Cottonwood. Shown for Each Sampling Date is the Range, Mean and One Standard Deviation on Each Side of the Mean. The Vertical Dashed Lines Indicate the Start and End of the Peeling Season

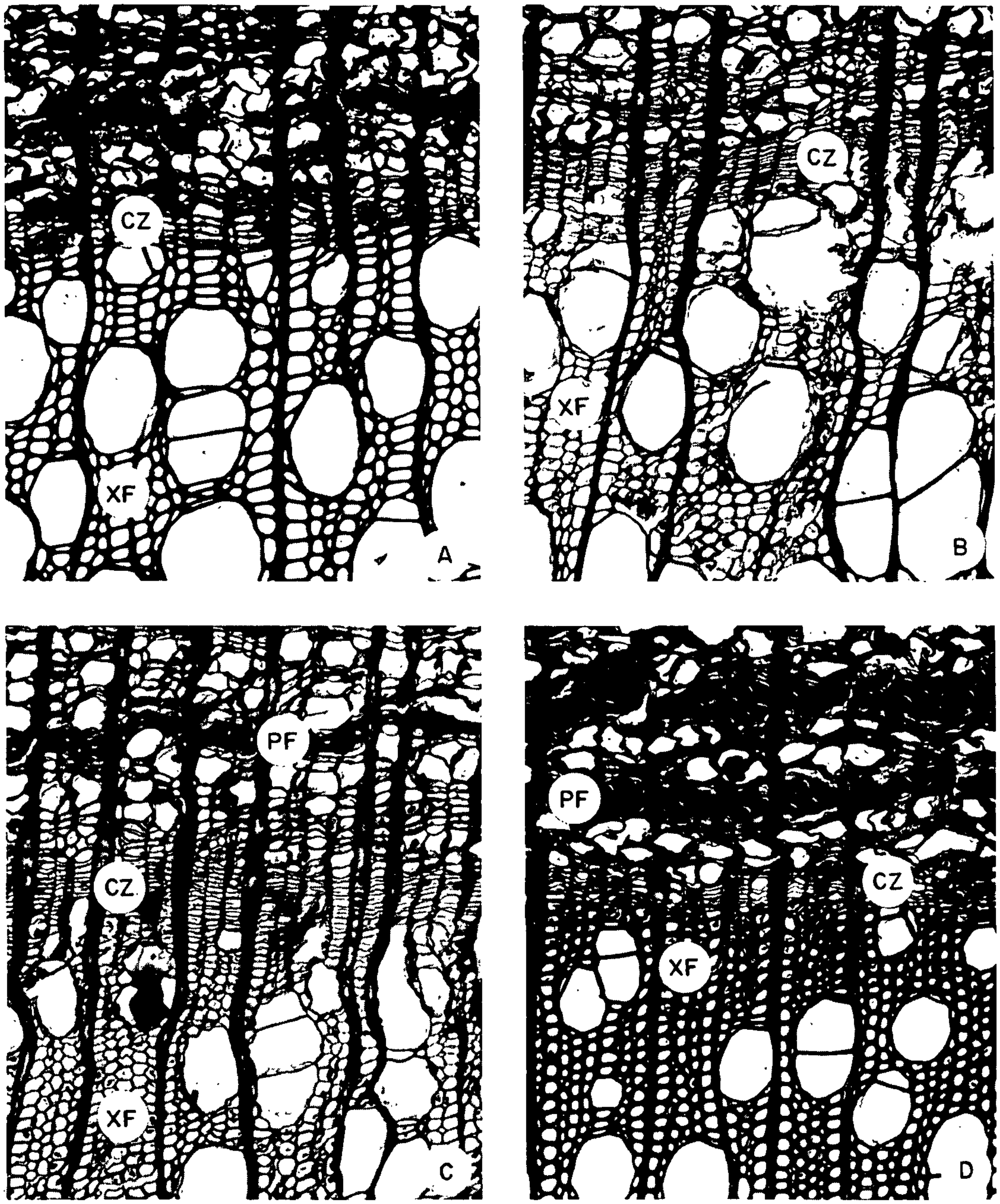

Figure 11. Illustrated in Cross Section are the Seasonal Changes that Occurred in the Cambium Zone of Cottonwood. A — February 1 Collection, Cambium Inactive, Cambium Zone (CZ) 3-4 Cells in Width; B — May 10 Collection, Cambium Active, Cambium Zone 12-14 Cells in Width with 6-8 Rows of Non-lignified Xylem Fibers and/or Vessels; C — July 12 Collection, Cambium Active, Cambium Zone 12-14 Cells in Width, 6-8 Rows of Nonlignified Xylem Fibers and/or Vessels Adjacent to the Cambium Zone; D — August 16 Collection, Cambium Dormant, Xylem Growth and Lignification for the Year Completed

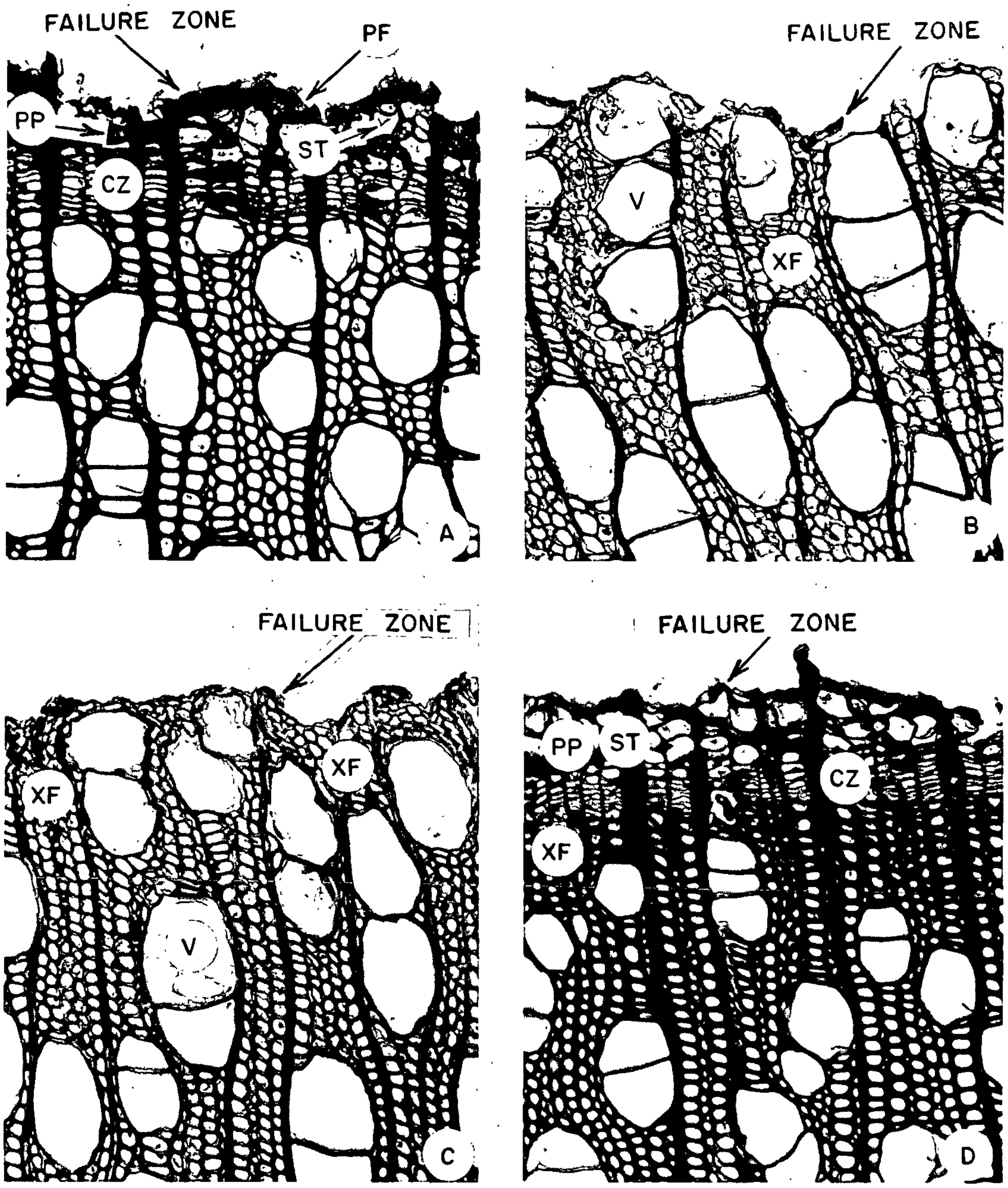

Figure 12. Illustrated are the Seasonal Changes in the Location of the Zone of Failure in Cottonwood. A — February 1 Collection, Failure in the Phloem Parenchyma and Sieve Tube Area (PP-ST) Just Outside the Cambium Zone (CZ) and Near Bands of Phloem Fibers (PF); B — May 10 Collection, Failure in Xylem Between Cambium Zone and Newly Formed Xylem Elements Showing Some Lignification; C — July 12 Collection, Failure in Xylem in Newly Formed Xylem Initials and Just Outside Xylem Elements Showing some Lignification; D — August 16 Collection, Failure Again in the Phloem Parenchyma — Sieve Tube Area (PP-ST) and Just Outside the Cambium Zone

stand being sampled on about March 1. Described below are brief summaries of the observations made on the seasonal morphological changes associated with changes in wood/bark adhesion.

February 1 — Cambium dormant; cambium zone 3-4 cells in width; failure occurred in the inner bark between the last formed sclerenchyma cells (thick-walled phloem fibers) and adjacent sieve tubes and parenchyma cells near the cambium zone (Fig. 11A and 12A). Estimated adhesion in the cambium zone was in excess of 7.2 kg./cm.^{2}

February 15 — Cambium dormant; some evidence of the start of cambium activity; morphology of the test samples not described; failure occurred in the inner bark region as on 2/1. Estimated adhesion in the cambium zone was in excess of 6.3 kg./cm.^{2}

March 1 — Cambium active; cambium activity apparently just starting; morphology of the test samples not described; failure believed to have occurred in the inner bark region as on 2/1 and 2/15. Estimated adhesion in the cambium zone was in excess of 6.2 kg./cm.^{2}

March 15 — Cambium dormant; tree flooded two weeks prior to sampling; cambium zone 3-4 cells in width; failure occurred in the inner bark, principally between the sieve tubes and parenchyma cells and next to the last formed band of phloem fibers just outside of the cambium zone. Estimated wood/bark adhesion was in excess of 9.2 kg./cm.^{2}

March 29 — Cambium dormant; tree still flooded; morphology of the test sample not described; failure believed to have occurred in approximately the same location as on March 15. Estimated wood/bark adhesion was in excess of 8.1 kg./cm.^{2}

April 19 — Cambium active; morphology of the test sample not described; failure believed to have occurred just outside of the cambium zone in the developing xylem initials; wood/bark adhesion in the cambium zone was 6.2 kg./cm.^{2}

May 10 — Cambium very active; cambium zone 12-14 cells in width; failure occurred in the xylem in the vicinity of the cambium zone, between nonlignified xylem initials and adjacent maturing xylem cells which show some lignification. Wood/bark adhesion in the cambium zone was 5.1 kg./cm.^{2}

June 14 — Cambium active, morphology of test samples not described; failure believed to have occurred in the same location as on May 10; wood/bark adhesion in the cambium zone was 5.1 kg./cm.^{2}

July 12 — Cambium active; cambium zone 12-14 cells in width; last 4-6 rows of xylem initials show no cell wall lignification, failure occurred in the same location as on May 10 and June 14. Wood/bark adhesion in the cambium zone was 4.4 kg./cm.^{2}.

August 2 — Cambium dormant; morphology of the test specimens not described; failure believed to have moved into the inner bark region; estimated wood/bark adhesion in the cambium zone was in excess of 9.8 kg./cm.^{2}

August 16 — Cambium dormant; cambium zone 4-5 cells in width; all xylem cells in this year's growth increments are fully mature and lignification is complete; failure occurred in the inner bark between sieve tubes and parenchyma cells and adjacent to a tangential band of phloem fibers. Estimated wood/bark adhesion in the cambium zone was in excess of 13.5 kg./cm.^{2}

August 30 — Cambium dormant; morphology of the test specimens not described; failure believed to have occurred in the inner bark as described for August 16 and February 1 before cambium activity started. Estimated wood/bark adhesion in the cambium zone was in excess of 12.6 kg./cm.^{2}

Wood/bark adhesion varied from 4.4 kg./cm.^{2} on July 12 to in excess of 13.5 kg./cm.^{2} on August 16. Based upon wood/bark adhesion measurements and morphological observations, the peeling season for the cottonwood stand being sampled near Mobile, Ala. ran from about April 8 to July 25 (108 days). Adhesion values during the peeling season averaged 5.2 kg./cm.^{2}, while in the dormant season they were in excess of 10.8 kg./cm.^{2} The length of the peeling season was complicated by the flooding of the stand from about March 2 until early April. Flooding delayed the start of the normal peeling season. Wood/bark adhesion values were lower for the two collection dates (2/15/71 and 3/1/71) prior to flooding. This reduction in adhesion was apparently due to hormone activity in the phloem which normally precedes cambium activity. The adhesion value trends suggest that had the site not flooded, cambium activity would have started sometime between March 1 and March 15. The flooding apparently delayed normal physiological development and not until about April 8 did adhesion values and the location of the failure zone indicate the peeling season was under way (values less than 7.0 kg./cm.^{2}).

Cottonwood, like the several other hardwoods tested, had a dormant season zone of failure in the inner bark sieve tubes and parenchyma cells just outside the cambium. Like aspen, the cottonwood tended to fail just inside or along the last-formed band of phloem fibers. During the peeling season, the zone of failure moved into the zone of newly-formed xylem and xylem initials. The zone of failure extended into the wood a maximum of 6 to 8 cells, always staying inside the cambium zone and outside the partially lignified xylem elements. Upon the cessation of cambium activity in the fall, the failure zone again moved into the inner bark.

The zones of weakness for cottonwood during the dormant season appeared to be the newly-formed immature parenchyma and sieve tubes of the inner bark and the thin-walled cells of the cambium zone. The presence of numerous thick-walled fibers and scattered groups of sclereids make it desirable to effect wood/bark separation as near as possible to the cambium zone. The inner bark fibers in cottonwood could be a useful raw material but the cost of pulping and the need to separate the fibers and sclereids are expected to limit such use. The extreme differences in structure of the wood and bark would suggest that any pulping of the two materials would require that each fraction be pulped separately.

SLASH PINE

Anatomical Structure of Wood and Bark

The wood (xylem) of slash pine (*Pinus elliottii*) consists of fiber tracheids aligned in radial rows, uniseriate and fusiform rays and longitudinal and transverse resin canals. Figure 13 illustrates some of the characteristics of the wood and inner bark of slash pine. The growth rings are very distinct, delineated by a pronounced band of thick-walled summerwood tracheids. The transition from spring to summerwood is abrupt. The tracheids have an average diameter of 40-45 µm. and an average length of 4.5-5.0 mm. The cell wall thickness of the earlywood fibers is approximately 2.0 µm., while the latewood fibers have a cell wall thickness of approximately 8.0 µm. The uniseriate rays are numerous and 1-8+ cells in height. The fusiform rays with transverse resin canals are 12+ cells in height. Marginal and interspersed dentate ray tracheids are present in both types of rays. The longitudinal resin canals average 90-150 µm. in diameter while the diameter of the transverse resin canals is approximately half this size. The canals are encircled with thin-walled epithelium. The ducts in the heartwood are frequently occluded with tylosoids.

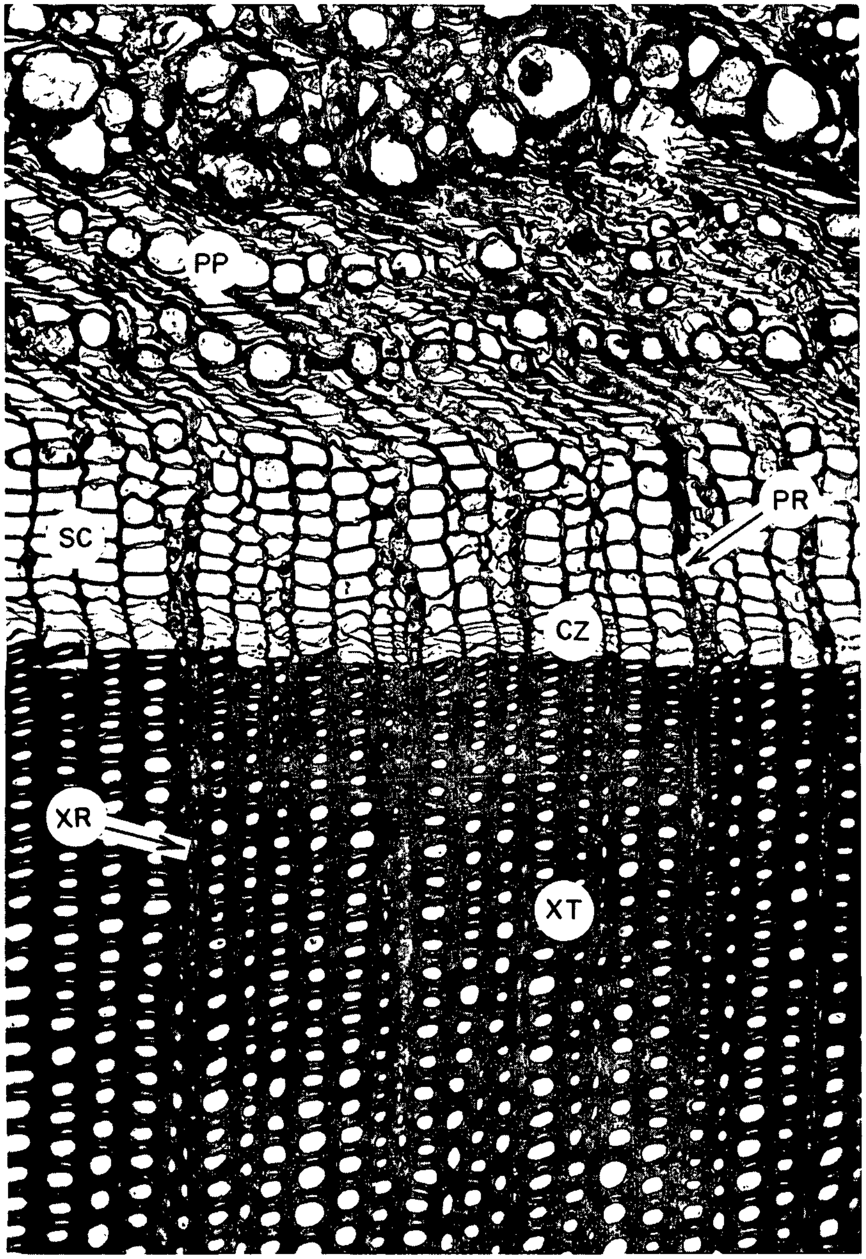

Figure 13. Cross Section of Slash Pine Taken During the Dormant Period. Illustrated are Sieve Cells (SC), Phloem Parenchyma (PP), Phloem Rays (PR), Cambium Zone (CZ), Xylem Rays (XR), and Summerwood Xylem Tracheids (XT)

The inner bark (secondary phloem) of slash pine is composed of radially aligned sieve cells interrupted by tangential lines of sporadically arranged parenchyma cells. These two types of cells are bordered radially by fusiform and uniseriate rays. Horizontal resin canals are present in the fusiform rays. There are no sclerenchyma cells present in most species of pine. The sieve cells near the cambium zone average approximately 35-40 µm. tangentially and 20-25 µm. radially. The radial measurement of these cells in the outer regions of the secondary phloem is less, due to collapsing caused by expanding phloem parenchyma cells in this area. The length of the sieve cells, according to Chang (1) range from 2.4 mm. to 4.6 mm. and have a mean length of 3.48 mm. Oval to circular-shaped sieve areas aligned in single vertical rows are predominantly on the radial walls. The cross sections of the phloem parenchyma cells in the proximity of the cambium zone are similar to the cross-sectional area of the newly-formed sieve cells in this region. Many of the parenchyma cells become expanded and are oval to circular in cross-sectional area after a few seasons of growth. These cells may attain a diameter of up to 100 µm. but their average diameter is between 40-50 µm. The length of a parenchyma strand is usually about the same length as the adjacent sieve cells. The uniseriate rays are usually approximately 10 cells in height (250-300 µm.). Horizontal resin canals are present in the fusiform rays. These canals are bordered with 3-4 thin-walled epithelial cells.

Seasonal Variation in Wood/Bark Adhesion

Seasonal sampling of slash pine wood/bark adhesion was initiated on February 1. Measurements were made throughout a major portion of the growing season and were discontinued after the August 30 samples were tested. Table IV summarizes both the morphological observations made on the test specimens and the results of the wood/bark adhesion measurements taken using the Instron testing procedure. Figure 14 graphically presents the seasonal variation encountered in the wood/bark adhesion measurements. Figure 15 illustrates the seasonal changes that occurred in the cambium zone and Fig. 16 demonstrates the accompanying changes that were found in the location of the zone of failure. Described below are the observations made on seasonal morphological changes that were associated with changes in wood/bark adhesion.

February 1 — Cambium dormant; morphology of the test samples was not described; failure appears to have occurred in the thin-walled sieve and parenchyma cells of the inner bark; estimated adhesion in the cambium zone was in excess of 7.9 kg./cm.^{2}

February 15 — Cambium dormant; cambium zone 5-6 cells in width; failure occurred in the phloem (inner bark) between sieve and parenchyma cells located approximately 1 mm. outside the cambium zone, Fig. 16A; estimated wood/bark adhesion in the cambium zone was in excess of 7.6 kg./cm.^{2}

March 1 — Cambium dormant; morphology of the test sample not described; failure appears to have occurred in the inner bark as on 2/15/71; wood/bark adhesion in the cambium zone was in excess of 7.6 kg./cm.^{2}

March 15 — Cambium dormant; cambium zone consists of five to six cells with innermost cells beginning to expand just prior to start of cambium activity (see Fig. 15B). Failure occurred one-half in the phloem parenchyma and sieve cells near the cambium and one-half in the expanding cambium zone cells just outside the fully mature tracheids of last year's growth ring. Wood/bark adhesion was 3.4 kg./cm.^{2}

TABLE IV

SUMMARY OF OBSERVATIONS ON SEASONAL VARIATION
IN SLASH PINE — MOBILE, ALABAMA

Date	Adhesion, kg./cm.^{2}		Cambium Activity[a]	Width Cambium Zone	New Xylem Cells		No. Immature Phloem Cells	Location of Zone of Failure	Additional Zones of Apparent Weakness
	Average	Standard Deviation			Total No.	No. Non-lignified			
2/1/71	7.8	0.42	D	5-6	0	0	3-4	Inner bark sieve and parenchyma cells near cambium	Cambium zone
2/15/71	7.6	0.57	D	5-6	0	0	3-4	Same as 2/1/71	Cambium zone
3/1/71	7.6	0.51	D	--	--	--	--	Same as 2/1/71	Cambium zone
3/15/71	3.4	0.25	A	5-6	0	0	3-4	Both in inner bark very near cambium and in expanding cambium zone	Inner bark and cambium zone
3/29/71	2.5	0.22	A	--	--	--	--	Newly formed xylem initials	Inner bark
5/10/71	4.5	0.31	A	6-8	45+	7-9	3-4	Same as 3/29/71	Inner bark
6/14/71	3.4	0.44	A	--	--	--	--	Same as 3/29/71	--
7/12/71	3.5	0.41	A	--	--	--	--	Same as 3/29/71	--
8/2/71	4.9	0.28	A	10-12	45+	3-4	3-4	Same as 3/29/71	Inner bark
8/16/71	7.8	0.64	A	--	--	--	--	Apparently in most recently formed xylem initials	--
8/30/71	14.6	1.24	D	5-6	65+	0	3-4	Between cambium zone and partially lignified tracheids	Inner bark

[a]A = active, D = dormant.

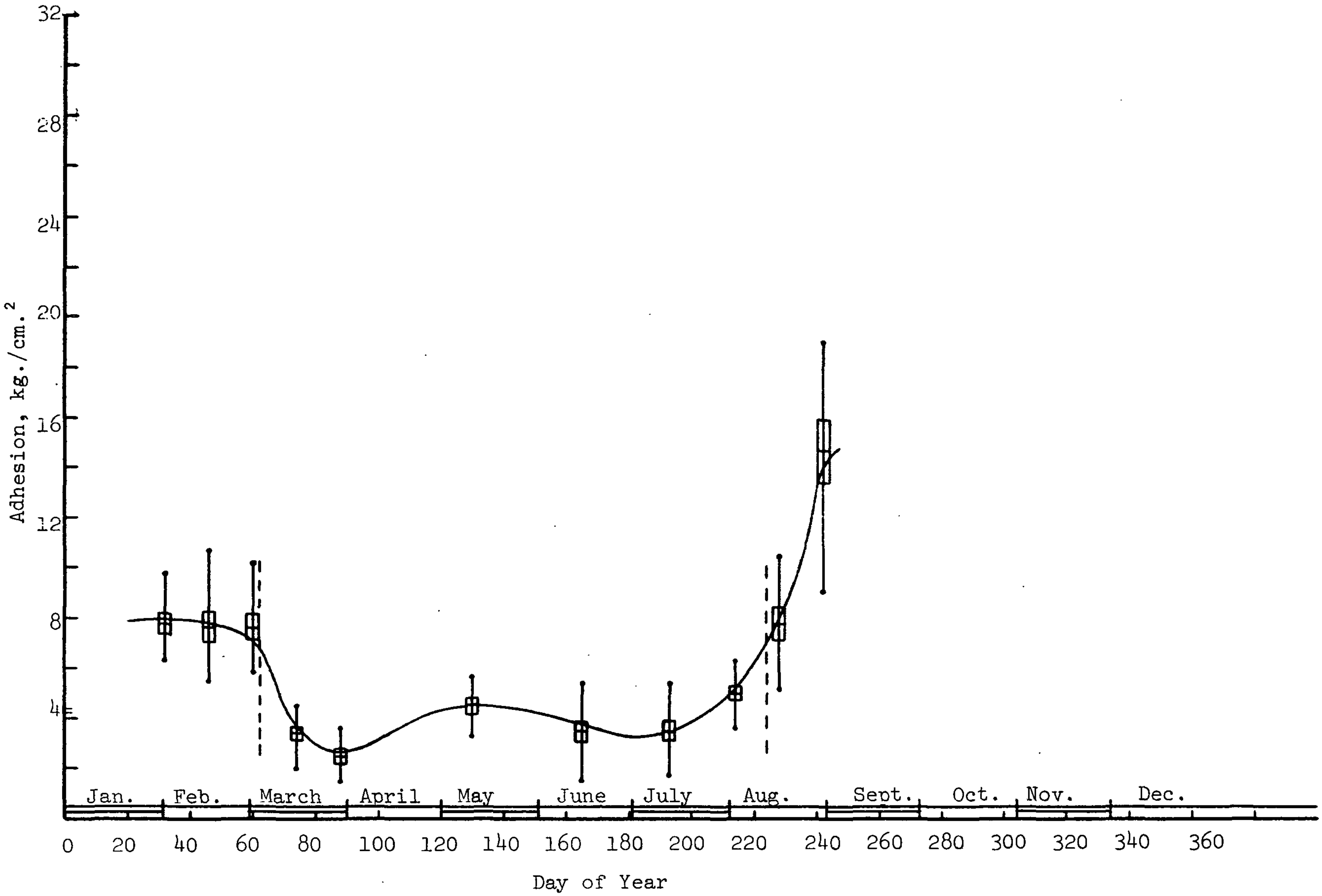

Figure 14. Seasonal Variation in Wood/Bark Adhesion of Slash Pine. Shown for Each Sampling Date is the Range, Mean and One Standard Deviation on Each Side of Mean. The Vertical Dashed Lines Indicate the Estimated Start and End of the Peeling Season

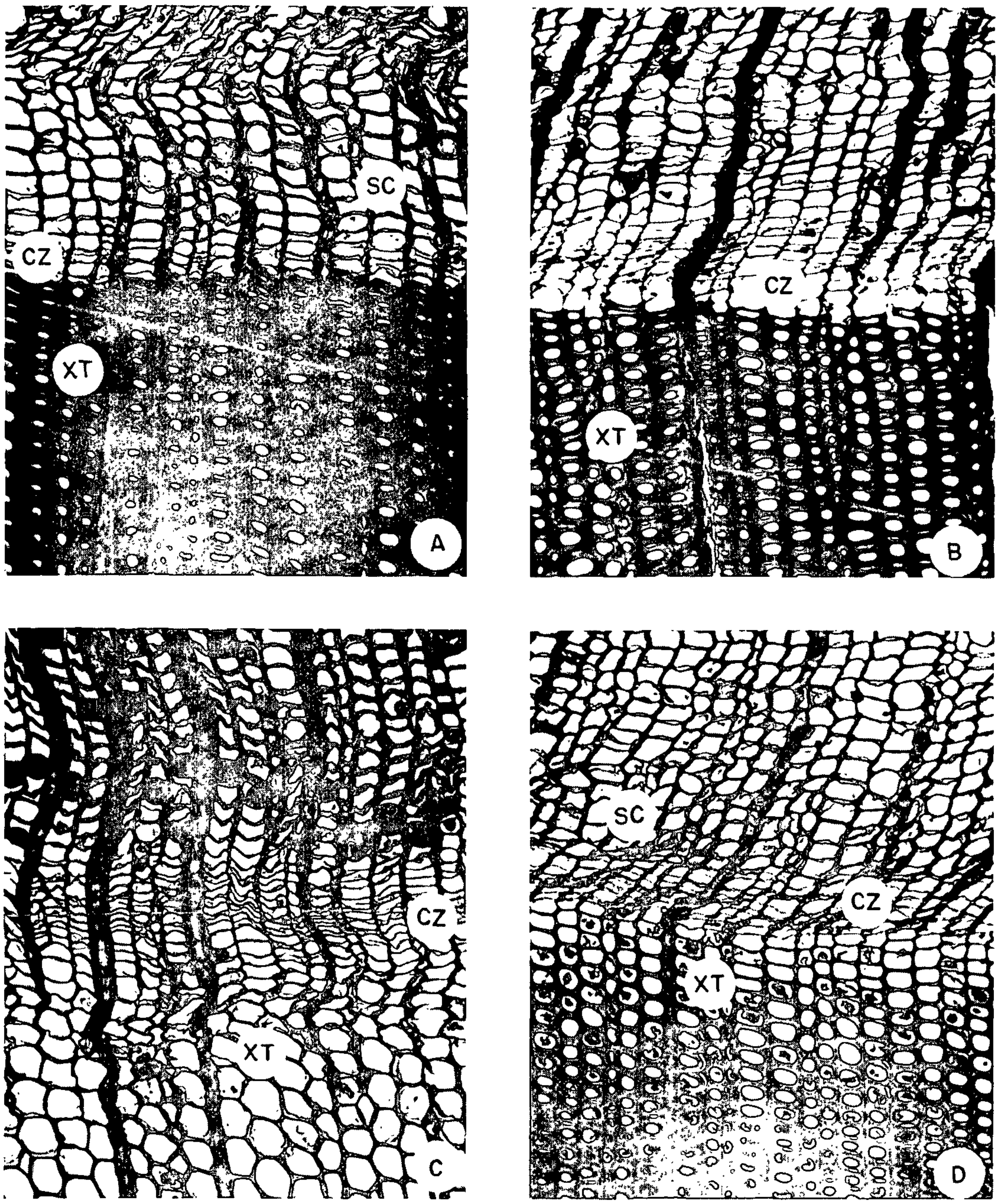

Figure 15. Illustrated are Seasonal Changes in the Condition of the Cambium Zone of Slash Pine; A — February 15 Collection, Cambium Dormant, Cambium Zone (CZ) 5-6 Cells in Width; B — March 15 Collection, Cambium Dormant, Cambium Zone (CZ) 5-6 Cells in Width with Innermost Cells Showing Evidence of Expansion Prior to Start of Cambium Activity; C — May 10 Collection, Cambium Active, Cambium Zone (CZ) 6-8 Cells in Width and Located Just Outside a Region of Newly Formed Xylem Tracheids (XT); D — August 30 Collection, Cambium Zone Very Narrow, Lignification of Last Formed Xylem Tracheids not Completed

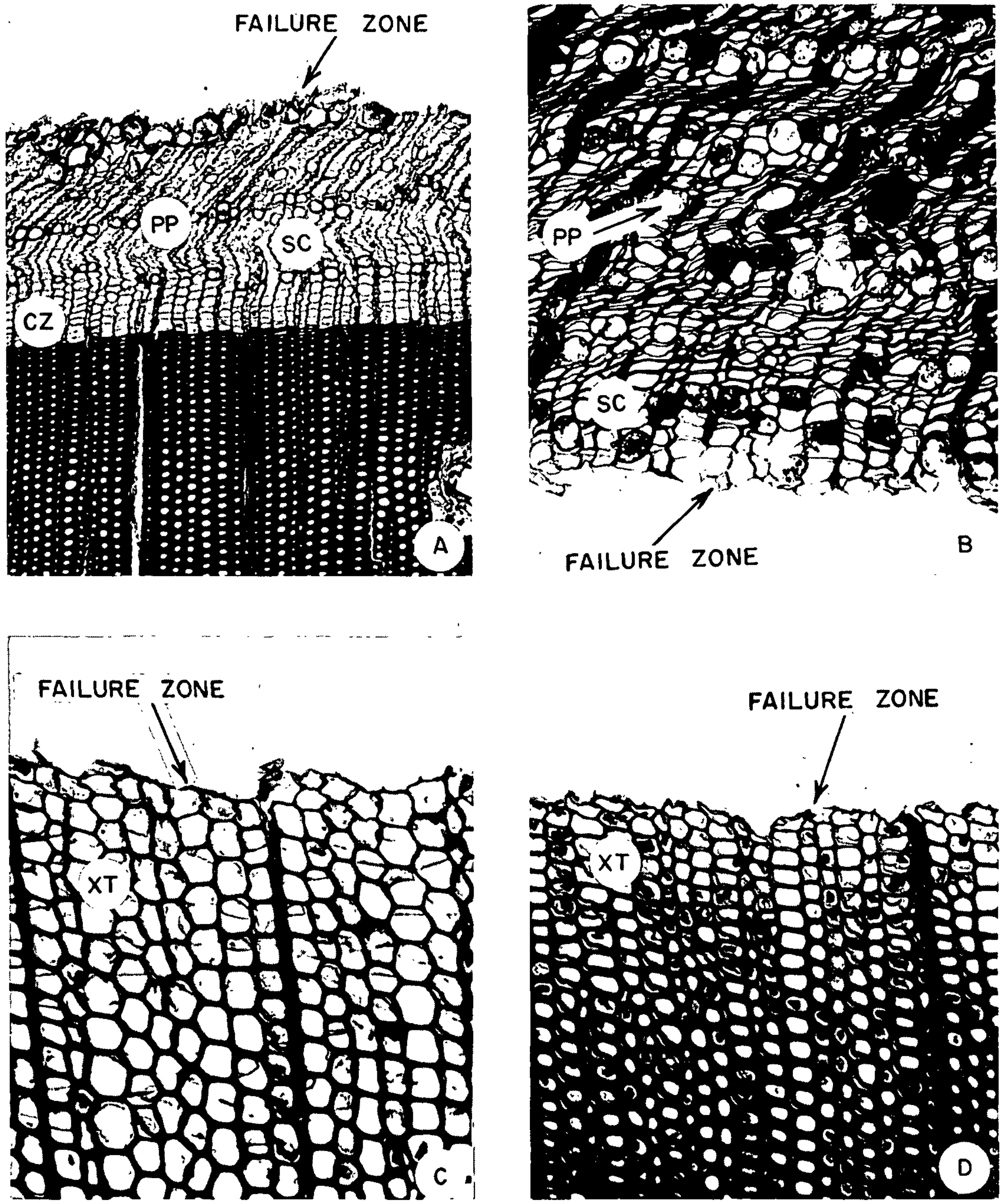

Figure 16. Seasonal Changes in the Zone of Failure in Slash Pine are Illustrated Above; A — February 15 Collection, Failure in Inner Bark in Sieve (SC) and Parenchyma Cells (PP) Well Outside the Cambium Zone (CZ); B — March 15 Collection, Failure Occurred in Inner Bark Sieve (SC) and Parenchyma Cells (PP) Near the Cambium Zone; C — May 10 Collection, Failure Occurred Just Inside the Cambium Zone Between Immature and Maturing Xylem Tracheids (XT); D — August 2 Collection, Cambium Still Active and Failure Occurred Between Xylem Initials and Immature Tracheids (XT) that Show Some Lignification

March 29 — Cambium active; morphology of the test samples not described; failure appears to have occurred just inside the cambium zone; wood/bark adhesion was 2.5 kg./cm.^{2}

May 10 — Cambium active; cambium zone 6-8 cells in width; failure occurred just inside the cambium zone between immature nonlignified xylem initials and maturing tracheids showing some lignification. Wood/bark adhesion was 4.5 kg./cm.^{2}

June 14 — Cambium active; morphology of test samples not described; failure appears to have occurred in the same location as on May 10. Wood/bark adhesion was 3.4 kg./cm.^{2}

July 12 — Cambium active; morphology of test samples not described; failure believed to have occurred as on May 10 and June 14; wood/bark adhesion was 3.4 kg./cm.^{2}

August 2 — Cambium active; cambium zone 10-12 cells in width; failure occurred as on May 10 between xylem initials and adjacent immature tracheids which show some lignification; wood/bark adhesion was 4.9 kg./cm.^{2}

August 16 — Cambium active; morphology of test samples not described; failure believed to have occurred as described for August 2; wood/bark adhesion was 7.8 kg./cm.^{2}

August 30 — Cambium zone very narrow (5-6 cells) and similar in width to dormant season samples taken in February (see Fig. 15). Failure occurred between the cambium zone and immature tracheids that show some lignification, although the secondary thickening has not been completed. Estimated adhesion in the cambium zone was in excess of 14.6 kg./cm.^{2}

Slash pine, like white spruce, has a fairly simple bark and wood structure as compared to the hardwoods and a relatively uncomplicated pattern of wood/bark adhesion. Based upon test values, cambium activity, and the width of the cambium zone, the bark peeling season was estimated to extend from March 3 to August 12 (adhesion values less than 7.0 kg./cm.^{2}). Wood/bark adhesion values during the peeling season averaged 3.5 kg./cm.^{2} Failure of the test specimens earlier in the season occurred in the inner bark sieve and parenchyma cells. As cambium activity and the width (number of cells) of the cambium zone increased, failure of the test specimens occurred between the xylem initials and the immature, partially lignified xylem tracheids. The zone of failure again apparently moves into the inner bark region after the cambium activity slows in the fall.

Morphological observations indicate that during the dormant season two zones of weakness exist and these are the sieve and parenchyma cell areas just outside the cambium and the cambium zone itself. Debarking methods that result in failure in either of the two zones should result in chips of satisfactory quality. The lack of thick-walled sclereid cells in the inner bark suggests inclusion of a moderate amount of inner bark should not have a detrimental effect on pulp and paper quality. The reader is reminded that the wood/bark adhesion values obtained during the season of low cambium activity (failure occurs in the inner bark) must be interpreted to mean that adhesion in the cambium zone is in excess of the test values obtained. The values obtained appear, as one might expect, to be a rough measure of inner bark strength (see the discussion on bark strength in the latter part of the report).

BARK STRENGTH MEASUREMENTS

As the work on the characterization of wood/bark adhesion for the various tree species progressed, it became evident that differences existed in the inner bark strength and that information on bark strength might be helpful in explaining dormant season adhesion results. It also appeared that appropriate bark strength information might suggest reasons for the difficulties being encountered in the commercial debarking of certain tree species as well as suggest possible mechanical techniques that could be used in solving wood/bark segregation problems.

There are a number of ways bark strength could be measured. However, because the sample preparation procedures and instrumentation had been worked out for shear parallel to the grain, preliminary information on bark strength was measured using the Instron tester and a procedure very similar to that developed for measuring wood/bark adhesion in the cambium zone. The test tabs used were the same size as for the wood/bark adhesion tests. The cuts made into the test specimen to cause failure in the desired zone extended into, and overlapped slightly (0.010 inch), in that part of the bark being tested. Measurements were made on both the inner and outer bark. The only exception involved white spruce where no outer bark measurements were made because the outer bark was too thin in the trees being tested. All measurements were made on freshly collected samples. The moisture content of the test samples were recorded and were found to be quite uniform, ranging from 31% for white birch to 39.2% for quaking aspen.

Table V summarizes the strength measurements made on the inner and outer bark of the 8 species under investigation. Of primary interest is the relationship that exists between dormant season wood/bark adhesion and the strength of the inner bark. Quite consistently the wood/bark adhesion failure zone during the dormant season was located in the inner bark region just outside the cambium. Based upon these observations, it was expected that a good correlation would result when inner bark strength and dormant season wood/bark adhesion data were compared. Table V makes such a comparison and, as the data indicate, the relationship was not very strong. The relationship seemed to hold quite well for hickory, cottonwood, oak, and slash pine but not for sugar maple and white birch. Careful examination of the inner bark failure zones of sugar maple and white birch make clear the reason for the lack of correlation between the two types of measurements is that two radially different types of failure zones are involved. The failure in the dormant season wood/bark adhesion test involves intact mature and partially mature sieve tube and parenchyma cells while the inner bark strength test involves crushed sieve tubes, parenchyma cells and clumps of sclereids. The lack of phloem fibers and the presence of sclereids and crushed sieve tubes is the reason for the weak inner bark strengths obtained.

TABLE V

BETWEEN SPECIES COMPARISONS OF WOOD/BARK ADHESION AND BARK STRENGTH

Species	Wood/Bark Adhesion, kg./cm.^{2}		Bark Strength, kg./cm.^{2}	
	Peeling Season	Dormant Season	Inner Bark	Outer Bark
Shagbark hickory	5.3	26.9	25.0	72.7
Eastern cottonwood	4.4	13.5	17.7	4.2[a]
Quaking aspen	6.4	11.4	9.0	4.9
Bur oak	5.8	9.6	4.5	7.0
White birch	5.1	12.0	1.6	9.8
Sugar maple	5.8	10.1	1.4	4.7
White spruce	5.0	11.0	7.4	--
Slash pine	3.5	9.1	6.4	5.2

[a]Strength low, test samples failed during preparation, data based upon a single test.

Considerable variation exists between species in the strength of both inner and outer bark. Shagbark hickory has the strongest inner and outer bark and of the species listed is generally considered to be the most difficult to debark. White birch and sugar maple, as previously discussed, were found to have extremely weak inner bark. The outer bark of white birch, as might have been predicted, was considerably stronger than the inner bark and was the second strongest of the outer barks tested. Cottonwood and aspen had the lowest outer bark strength, suggesting they would behave similarly under mechanical bark treatments that employed a shearing action. Maple also had a low outer bark strength but because of an extremely low inner bark strength would be expected to behave in a somewhat different manner than aspen and cottonwood.

The preliminary measurements on bark strength answered some of the questions regarding debarking and raised others. Because inner bark strength and inner bark morphology appeared to be "the key" to dormant season mechanical debarking, observations are proposed on additional pulpwood species in an effort to further clarify some of the anomalies encountered. Hopefully, these additional observations, along with additional studies on ways of reducing wood/bark adhesion, will put into proper perspective the potential of chemical, thermal, and mechanical debarking of wood chips.

BETWEEN SPECIES COMPARISONS

The usefulness of making observations on a number of tree species is that it is then possible to compare like species or like areas within the species and determine whether behavior is comparable. Comparisons between species differing greatly in their morphology provide a chance to "zero in" on those morphological characteristics that are associated with the problem under consideration. In this case the basic problem is "excessive wood/bark adhesion during the dormant season." For the reader's convenience, the 8 tree species upon which wood/bark adhesion measurements have been completed are summarized in the previously discussed Table V and in Table VI. Included in the tables are summaries of dormant season and peeling season adhesion values, principal zones of failure during the dormant and peeling seasons, and information on bark morphology.

One point of interest is the remarkable between species similarity of wood/bark adhesion during the peeling season. Slash pine and cottonwood had the lowest wood/bark adhesion (3.5 and 4.4 kg./cm.^{2}). Quaking aspen, which is generally considered by Lake States standards as easy to peel during the peeling season, had the highest cambium zone wood/bark adhesion (6.4 kg./cm.^{2}). Accompanying the overall similarity in peeling season adhesion values is the consistent location of the failure zone during the peeling season. In all instances the peeling season failure zone was located in either the cambium zone or the partially mature, nonlignified xylem and xylem initials.

Dormant season wood/bark adhesion values are of primary interest in this investigation and large between species differences were encountered. The differences

TABLE VI

MORPHOLOGY OF INNER BARK AND ZONE OF FAILURE

Species	Zone of Failure		Morphology of Inner Bark		Number of Large Rays
	Peeling Season	Dormant Season	Inside Zone of Failure	Outside Zone of Failure	
Shagbark hickory	Cambium zone[a]	Between bands of phloem fibers and immature parenchyma cells	Phloem fibers, immature parenchyma and scattered sieve tubes	Many phloem fibers, scattered sieve tubes and bands of phloem parenchyma cells	Few
Eastern cottonwood	Cambium zone[a]	Immature parenchyma and sieve tubes of inner bark	Phloem fibers, immature and mature sieve tubes and parenchyma cells	Many phloem fibers, scattered sclereids, sieve tubes and parenchyma cells	None
Quaking aspen	Cambium zone[a]	Same as above	Same as above	Same as above except fewer fibers	None
Bur oak	Cambium zone[a]	Same as above	Immature and mature phloem parenchyma and crushed sieve tubes	Same as aspen except more crushed sieve tubes and sclereids in broad rays	Many
White birch	Cambium zone[a]	Same as above	Scattered sclereids, immature and mature sieve tubes and parenchyma	Numerous sclereids, crushed sieve tubes, parenchyma cells	Many
Sugar maple	Cambium zone[a]	Same as above	Immature and mature phloem parenchyma and crushed phloem sieve tubes	Same as above except more sclereids	Many[b]
White spruce	Cambium zone[a]	Immature inner bark parenchyma and sieve cells	Parenchyma and sieve cells	Parenchyma and sieve cells with scattered small groups of sclereids	None
Slash pine	Cambium zone[a]	Same as above	Same as above	Parenchyma and sieve cells	None

[a] In the cambium zone or the newly-formed nonlignified xylem cells inside the cambium zone.

[b] Mostly medium-sized rays.

in adhesion values appeared, in part, to be related to inner bark morphology. Cottonwood and aspen, for example, are very similar in inner bark morphology, having an inner bark where prominent bands of phloem fibers alternate with bands of thin-walled sieve tubes and parenchyma cells. For the two sources of trees examined, the bands of phloem fibers are more evident (distance between successive bands of fibers was less) in cottonwood than in aspen. Dormant seasons wood/bark adhesion values were quite similar for aspen and cottonwood (11.4 vs. 13.5 kg./cm.^{2}) while the inner bark strength of eastern cottonwood was approximately twice that of aspen. The dormant season failure zone fell in essentially identical locations for the two species, being located in the most recently formed immature sieve tube and parenchyma cell zones just outside the cambium and along the first-formed band of phloem fibers. The much higher inner bark strength of cottonwood, although not examined carefully at this point, is believed to be associated with the closer spacing of the bands of phloem fibers in the mature inner bark of cottonwood. The reader is reminded that only a limited number of trees have been examined and additional sources of aspen and cottonwood would need to be processed before we are sure the differences described are universally true.

Sugar maple and white birch were found to have very similar dormant season wood/bark adhesion values. They also had comparable and very weak inner bark strength. The lack of correlation between the inner bark strength and the dormant season wood/bark adhesion values appear to be related to differences in the location of the test zones. The dormant season wood/bark adhesion values appear to be a test of the strength of the innermost layers of phloem parenchyma and sieve tube elements of the inner bark and test very similar elements for all of the hardwoods examined in this study, except perhaps hickory. The strength test of the inner bark measures the strength and adhesion between the mature elements of the inner bark and more closely reflects the differences in morphology. The "mature" inner bark of white birch and sugar maple contain essentially no phloem fibers, have an abundance of thick-walled sclereids and, during bark development, most of the sieve tubes and parenchyma cells become crushed. A group of sclereids apparently contribute little to inner bark strength (shear parallel to the grain) and the low strength values apparently are the result of the several factors mentioned above.

White spruce and slash pine, the two conifers tested, also contributed to our understanding of wood/bark adhesion and bark peeling problems. Slash pine had the lowest peeling season and lowest dormant season adhesion of the species tested. White spruce was intermediate in peeling season and dormant season adhesion. Location of failure zones was identical to that of the hardwoods studied. Neither species have phloem fibers and as a result have relatively weak inner bark strength. The lack of sclereids in the inner bark of slash pine indicate moderate amounts of inner bark attached to chips should have little influence on pulp strength properties.

Bur oak had slightly lower dormant season wood/bark adhesion values than the other hardwood species tested and was intermediate between birch-maple and aspen-cottonwood in the strength of the inner bark. The dormant season failure zone was very similar to that of aspen and cottonwood in that failure occurred in the innermost zone of phloem sieve tubes and parenchyma cells and adjacent to bands of phloem fibers. The inner bark morphology appears to be well correlated with the low to intermediate (4.5 kg./cm.^{2}) inner bark strength values obtained. The inner bark has both phloem fibers, which apparently increased the strength, and sclereids, which contribute little to the strength. Also, a high proportion of the sieve tubes and phloem parenchyma in the inner bark are crushed suggesting that this too, as in the case of birch and maple, resulted in reduced inner bark strength.

Oak, birch, and maple have many prominent xylem and phloem rays and the question arises regarding the lack of influence of such rays on the wood/bark adhesion values and inner bark strength values. A closer evaluation makes it appear that the nature of the shear test involved (parallel to the grain) could be the reason. The shear test is parallel to the grain and since the rays are oriented across the shear plane but have their widest dimension parallel rather than across the zone of failure, it appears any influence they might exert is minimized. The occurrence of ray stubs and pull-out areas along the failure zone in sugar maple and bur oak (Progress Report 2) appears to support this line of reasoning. A shear test similar to that presently employed but in the cross grain direction would maximize the influence of the ray cells on adhesion and shed further light on the importance of rays in wood/bark adhesion.

Shagbark hickory, a species of only minor importance as a source of pulpwood, turned out to be the species that contributed the most to our understanding of factors influencing wood/bark adhesion. Shagbark hickory had the highest dormant season adhesion (26.9 kg./cm.^{2}), the highest inner bark strength (25 kg./cm.^{2}) and the highest outer bark strength (72.7 kg./cm.^{2}), while during the peeling season wood/bark adhesion was comparable to the other species tested. The presence of numerous narrow bands of phloem fibers and the scattered arrangement of sieve tubes apparently were the factors contributing to the high dormant season adhesion and the high bark strength values obtained. Shagbark hickory is reported to be difficult to peel mechanically and results of the investigation indicate higher inner and outer bark strength are major contributing factors. The large number of fibers and the absence of sclereids in the inner and outer bark of hickory (Fig. 17) suggest hickory bark might be considered as a possible special source of thick-walled fibers. However, before such as approach is seriously considered, fiber strength should be checked in view of the gelatinous nature of the fibers.

Figure 17. Isolated Inner Bark Fibers, Phloem Fibers (PP), of Shagbark Hickory. Fiber Length Averages 1.0 mm.

The wood/bark adhesion data continued to emphasize that, during the dormant season, methods of reducing adhesion on chip samples should concentrate on the cambium zone and/or the sieve tube and parenchyma cell zone just outside the cambium. The morphological data also suggest that in those species which have minimum numbers of thick-walled sclerenchyma cells (fibers and sclereids), leaving a moderate amount of inner bark will have little influence on required cooking conditions, speck problems or pulp strength properties. Species falling in this category include: slash pine, white spruce and white birch. Large numbers of sclereids in the inner bark of maple and large numbers of thick-walled phloem fibers in hickory, cottonwood and aspen restrict the amount of inner bark that can be accepted for these species. The sclereids are commonly associated with speck problems in paper while the bands of thick-walled fibers are expected to require increasing the severity of cooking conditions.

PLANS

Measurements of seasonal variation in wood/bark adhesion have been completed for the eight species under investigation. The seasonal variation in the location of the zone of failure and the morphological changes associated with variations in wood/bark adhesion have been documented. The plans for the next project period involve renewing efforts to develop techniques for reducing "dormant season" wood/bark adhesion on chip samples.

Preliminary investigations into the reduction of wood/bark adhesion were described in Progress Report 2. This work indicated that thermal and mechanical procedures seemed to have the most promise and these approaches will be investigated further using quaking aspen, slash pine, white spruce, shagbark hickory, and cottonwood. Additional trials with pulping chemicals are presently under way and plans also include trials using ultrasonic and microwave treatments.

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GLOSSARY

Epithelium. Excreting parenchymatous tissue surrounding the cavity of resin and gum canals.

Fusiform ray. Spindle-shaped ray, as viewed in a tangential section of wood, containing a resin canal.

Gelatinous fiber. Fiber, the inner wall of which is more or less gelatinous, or jellylike.

Inner bark. Tissues in the cylindrical axis of a tree immediately outside the cambium; includes the region of the secondary phloem from the cambium to the last-formed periderm.

Outer bark. Tissues in the cylindrical axis of a tree immediately outside the inner bark; includes the tissues from the last-formed periderm to the outer surface of the bark.

Parenchyma. Tissue consisting of short, relatively thin-walled cells, generally with simple pits; concerned primarily with storage and distribution of carbohydrates.

Periderm. Term applied to the cork cambium (phellogen) and the tissues derived from the cork cambium.

Phloem. Inner bark; principal tissue concerned with the distribution of elaborated foodstuffs, characterized by the presence of sieve tubes.

Ray. Ribbon-shaped strand of tissue extending in a radial direction across the grain.

Resin canal. An intercellular space, often bordered by secreting cells, containing resin or turpentine.

Sclereid. See Sclerenchyma.

Sclerenchyma. Mechanical tissue consisting of cells with thick, lignified walls and small lumens. If the cells are elongated, they are called fibers and usually occur in bundles. When the cells are oval or rounded, they are called sclereids. These occur singly or in groups.

Sieve tube. A characteristic element of phloem. It translocates food materials synthesized into plant. The cells are living, thin-walled and in longitudinal rows. They are connected by perforations in their transverse walls, through which pass strands of cytoplasm.

Storied. Arranged in tiers or in echelon, as viewed on a tangential surface or in a tangential section.

Tracheid. Fibrous lignified cell with bordered pits and imperforate ends; in coniferous wood, the tracheids are very long (up to 7+ mm.) and are equipped with large, prominent bordered pits on their radial walls; tracheids in hardwoods are shorter fibrous cells (seldom over 1.5 mm.) are as long as the vessel segments with which they are associated, and possess small bordered pits.

Tylosoids. Balloonlike structures in resin canals resembling tyloses in hardwoods.

Uniseriate. Arranged in a single row, series, or layer. Also said of a vascular ray which is one cell wide in cross section.

Vessel. Composite, and hence articulated, tubelike structure found in porous wood, arising through the fusion of the cells in a longitudinal row through the partial or complete disappearance of the cross walls.

Xylary initials. The newly formed vascular tissue which conducts water and mineral salts throughout the plant and provides mechanical support.

Xylem. Wood. The vascular tissue which conducts water and mineral salts throughout the plant and provides mechanical support. It consists of vessels, and/or tracheids, fibers, and some parenchyma.